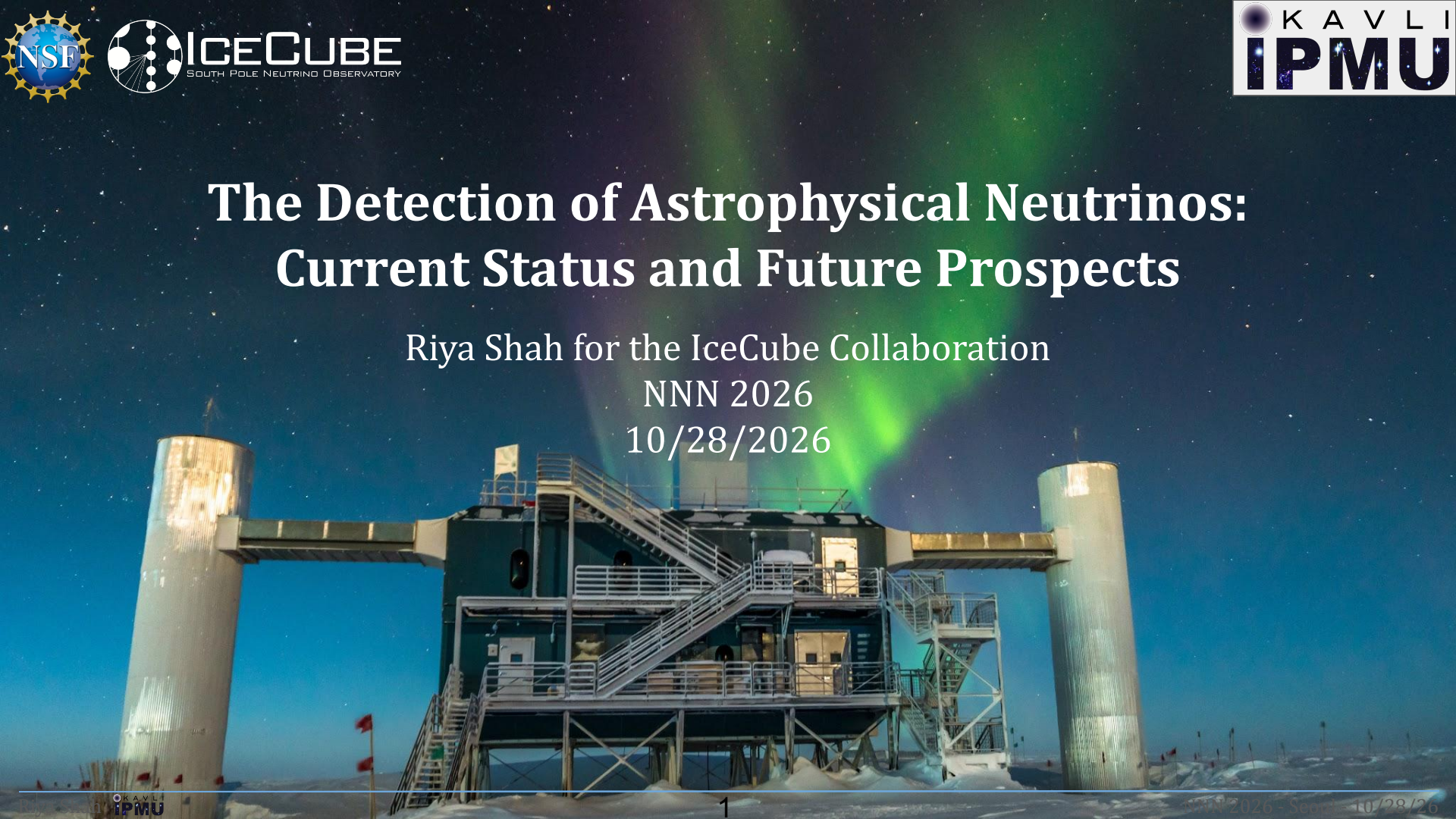


The Detection of Astrophysical Neutrinos: Current Status and Future Prospects

Riya Shah for the IceCube Collaboration

NNN 2026

10/28/2026

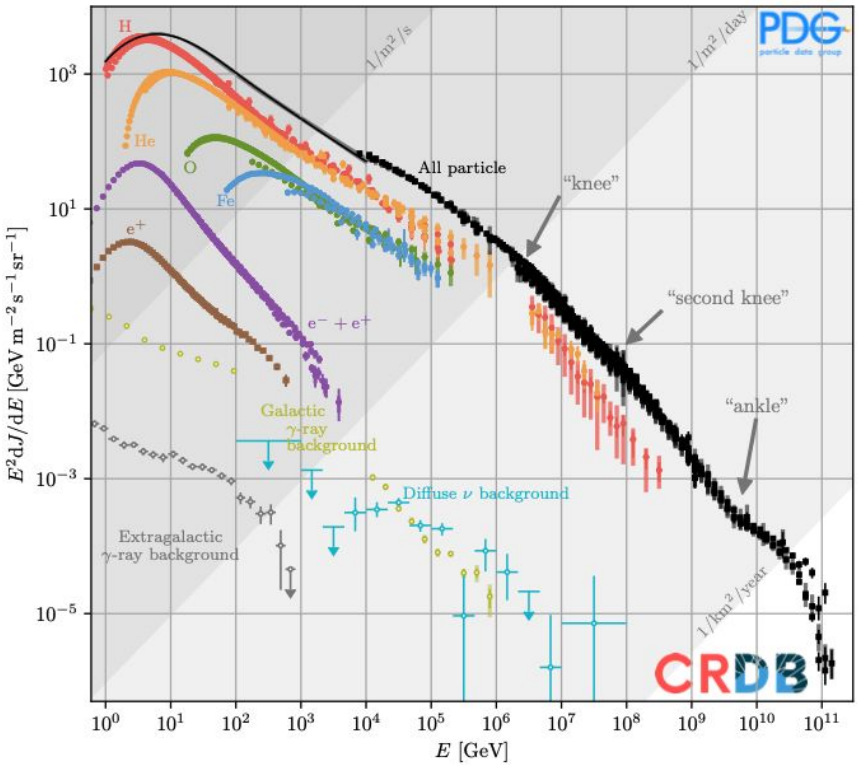
Outline

- Multi-Messenger Astronomy with Neutrinos
  - Origins of high-energy cosmic rays
- Cosmic Neutrino Spectrum
  - Highlights from astrophysical neutrino source searches
- Future Experiments
- Summary

Multi-Messenger Astronomy with Neutrinos

Multi-Messenger Astronomy: Cosmic Rays (CR)

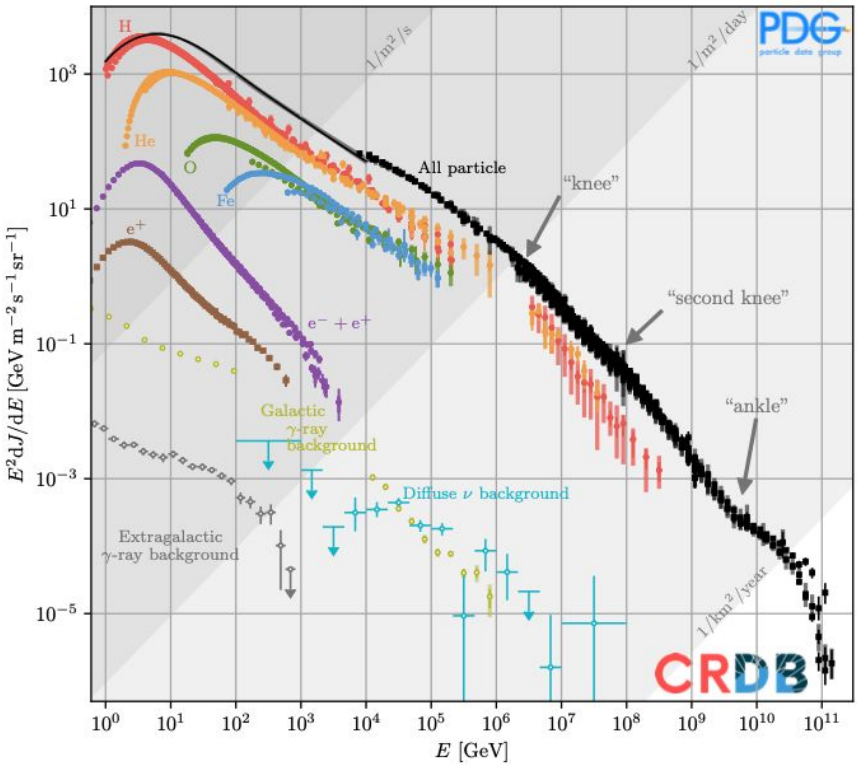
- High-energy, relativistic sub-atomic particles or nuclei



S. Navas et al. Review of particle physics. *Physical Review D*, 110(3):030001, 2024.

Multi-Messenger Astronomy: Cosmic Rays (CR)

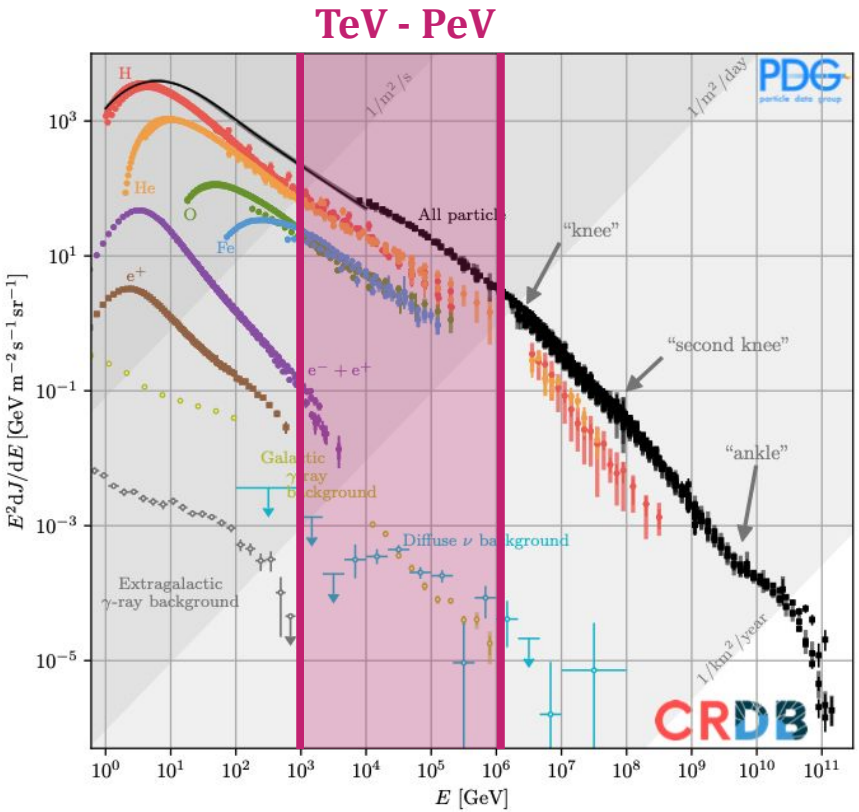
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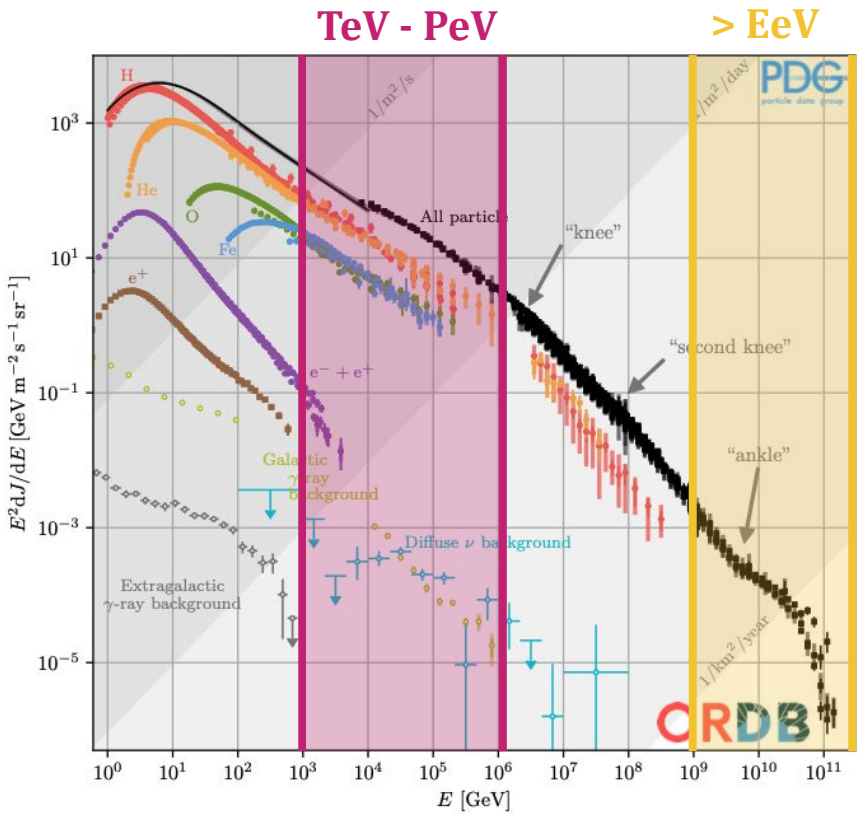
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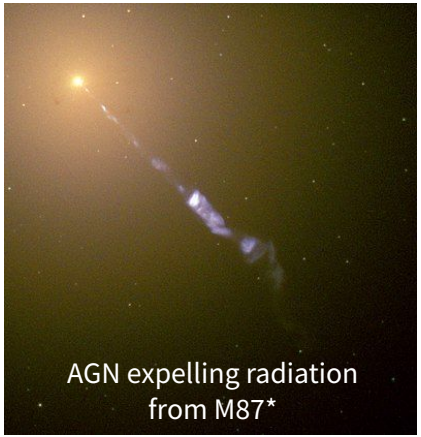
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S. Navas et al. Review of particle physics. *Physical Review D*, 110(3):030001, 2024.

Potential High-Energy Cosmic-Ray Sources

- Active Galactic Nuclei (AGN)
  - Blazars
  - Seyferts
  - X-Ray Bright

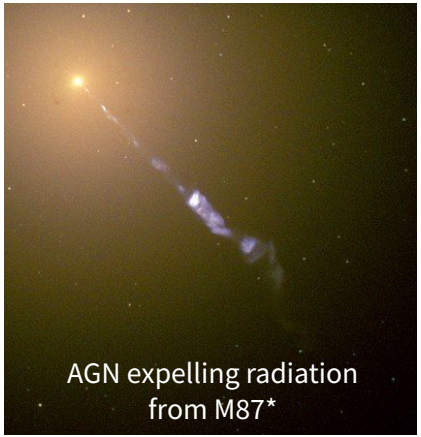


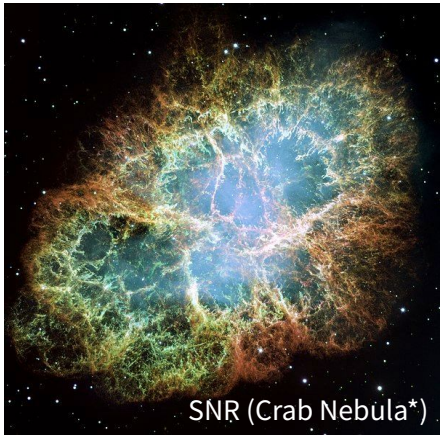
AGN expelling radiation from M87*

*Credit: NASA

Potential High-Energy Cosmic-Ray Sources

- Active Galactic Nuclei (AGN)
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- Supernova Remnants (SNRs) & Supernovae

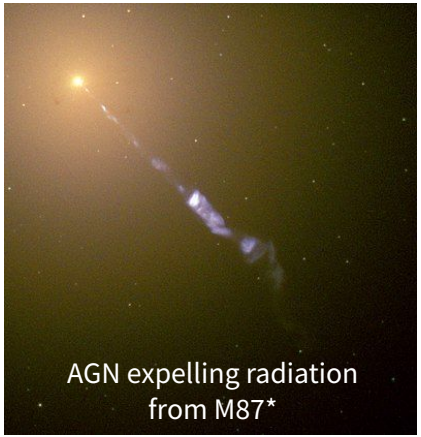


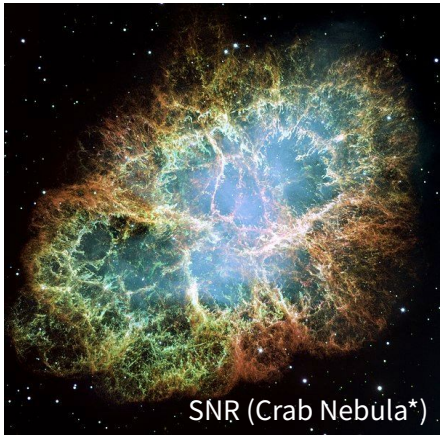


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Potential High-Energy Cosmic-Ray Sources

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- Gamma-ray Bursts (GRBs)


AGN expelling radiation from M87*

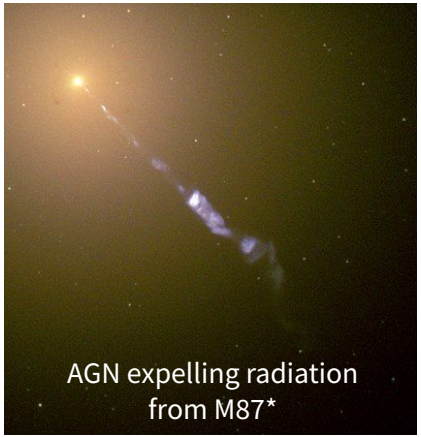

SNR (Crab Nebula*)

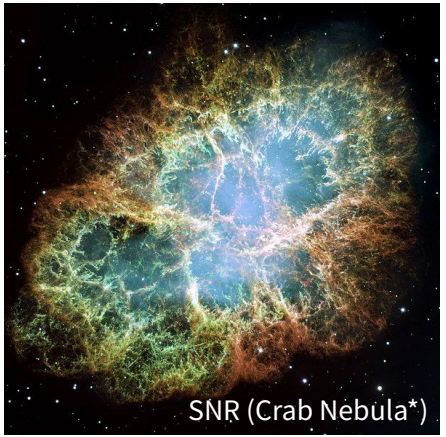

Artist Rendition of gamma-ray burst*

*Credit: NASA

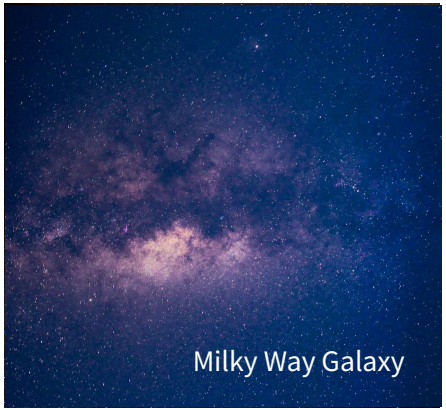
Potential High-Energy Cosmic-Ray Sources

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- Supernova Remnants (SNRs) & Supernovae
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- Galactic plane (Milky Way)


AGN expelling radiation from M87*


SNR (Crab Nebula*)

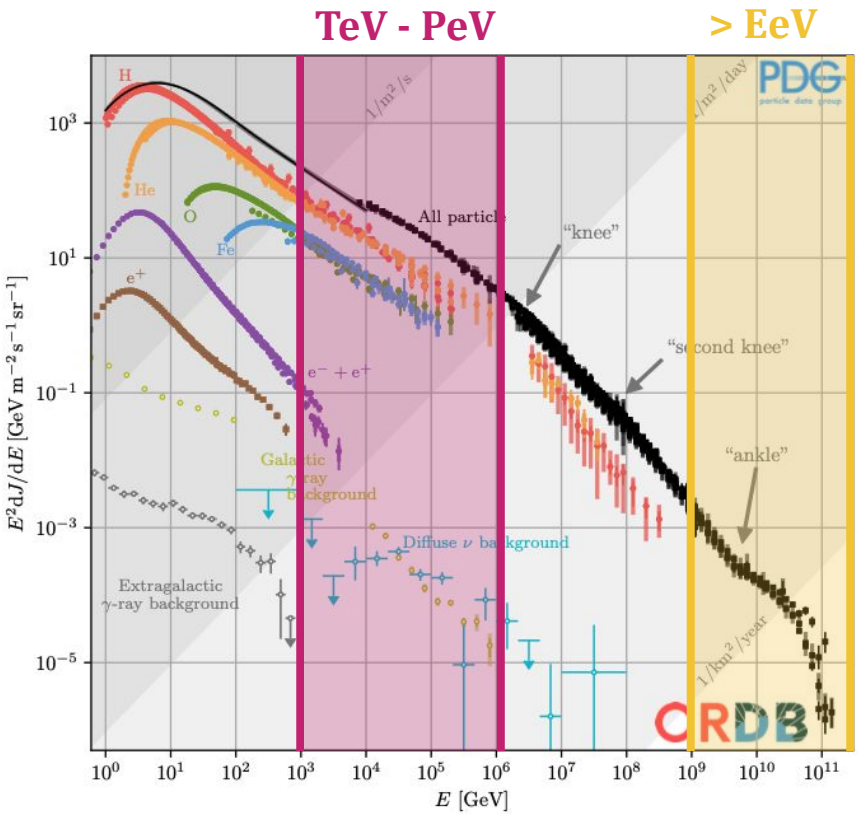

Artist Rendition of gamma-ray burst*


Milky Way Galaxy

*Credit: NASA

Why is it difficult to identify CR sources?

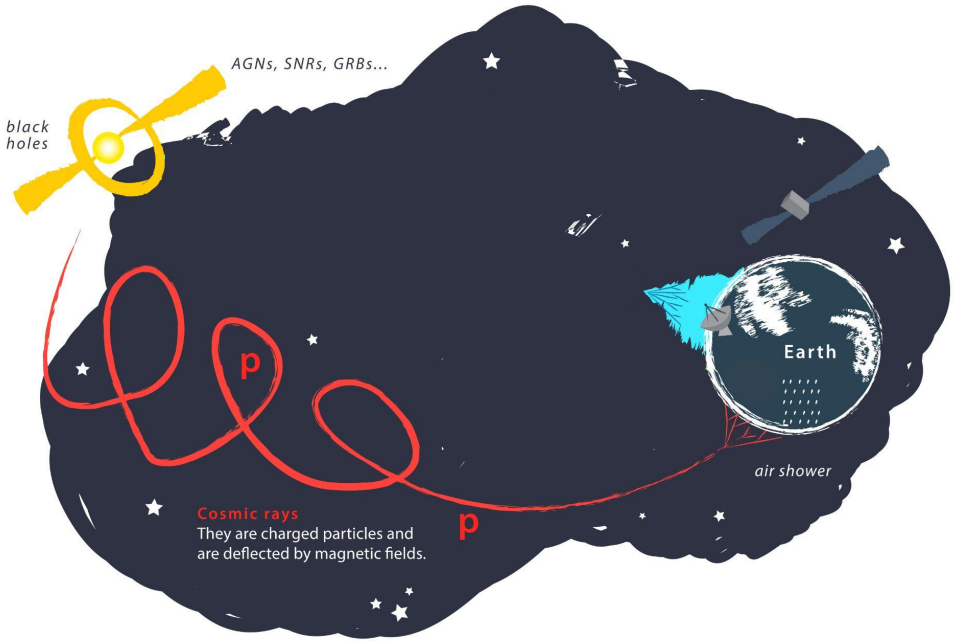
- High energy cosmic-rays are rare



S. Navas et al. Review of particle physics. *Physical Review D*, 110(3):030001, 2024.

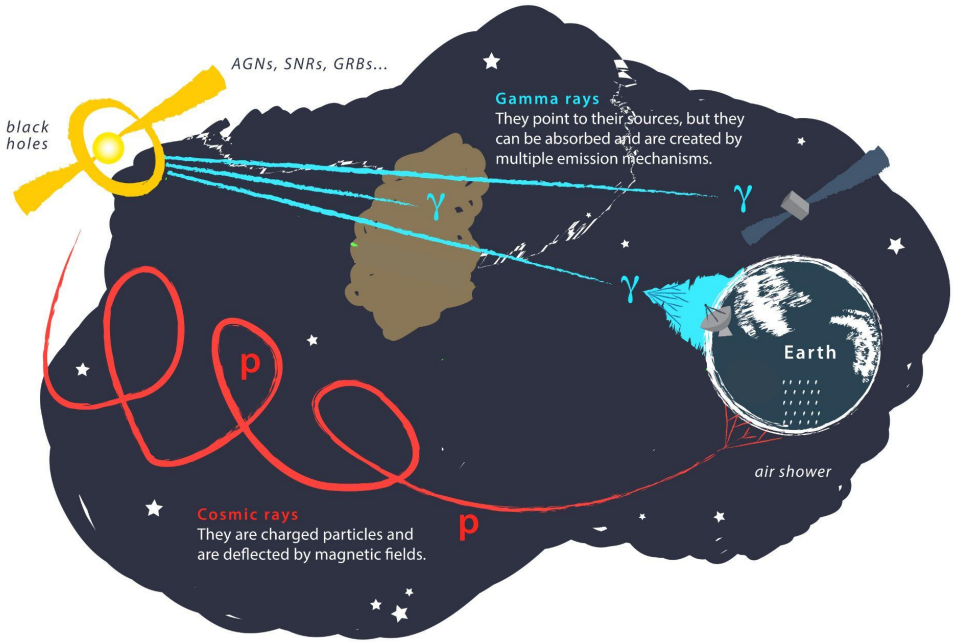
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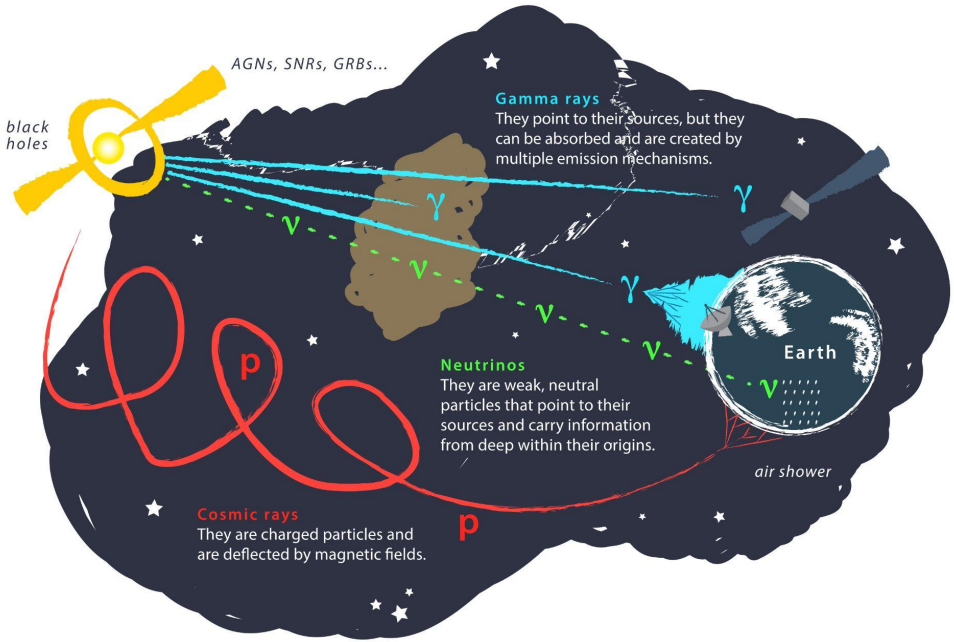
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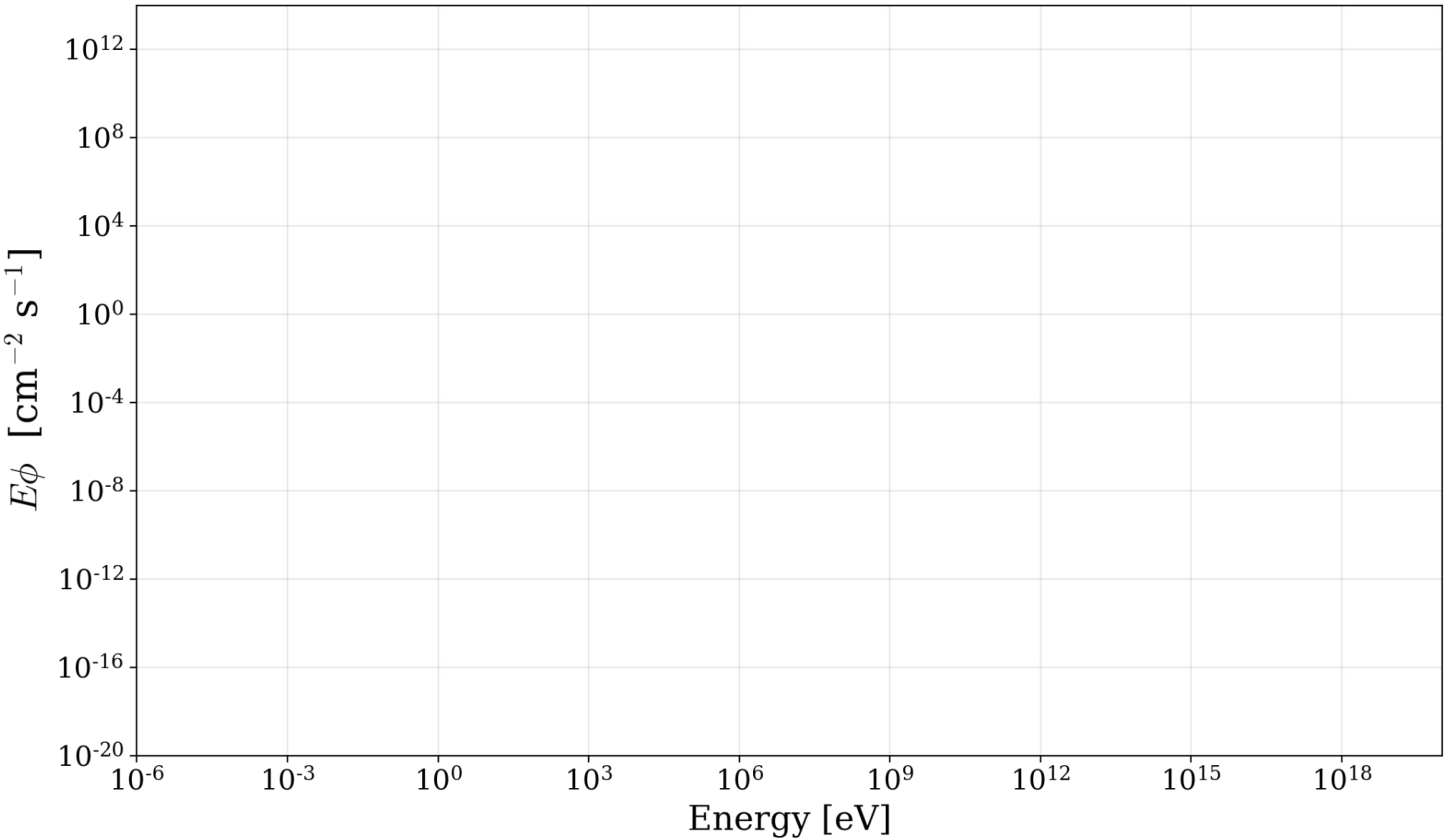
Why is it difficult to identify CR sources?

- High energy cosmic-rays are rare
- Charged particles are deflected by magnetic fields
- Photons interact with other photons and matter
- Neutrinos are not deflected and don't often interact with matter!



*Not discussed in this talk

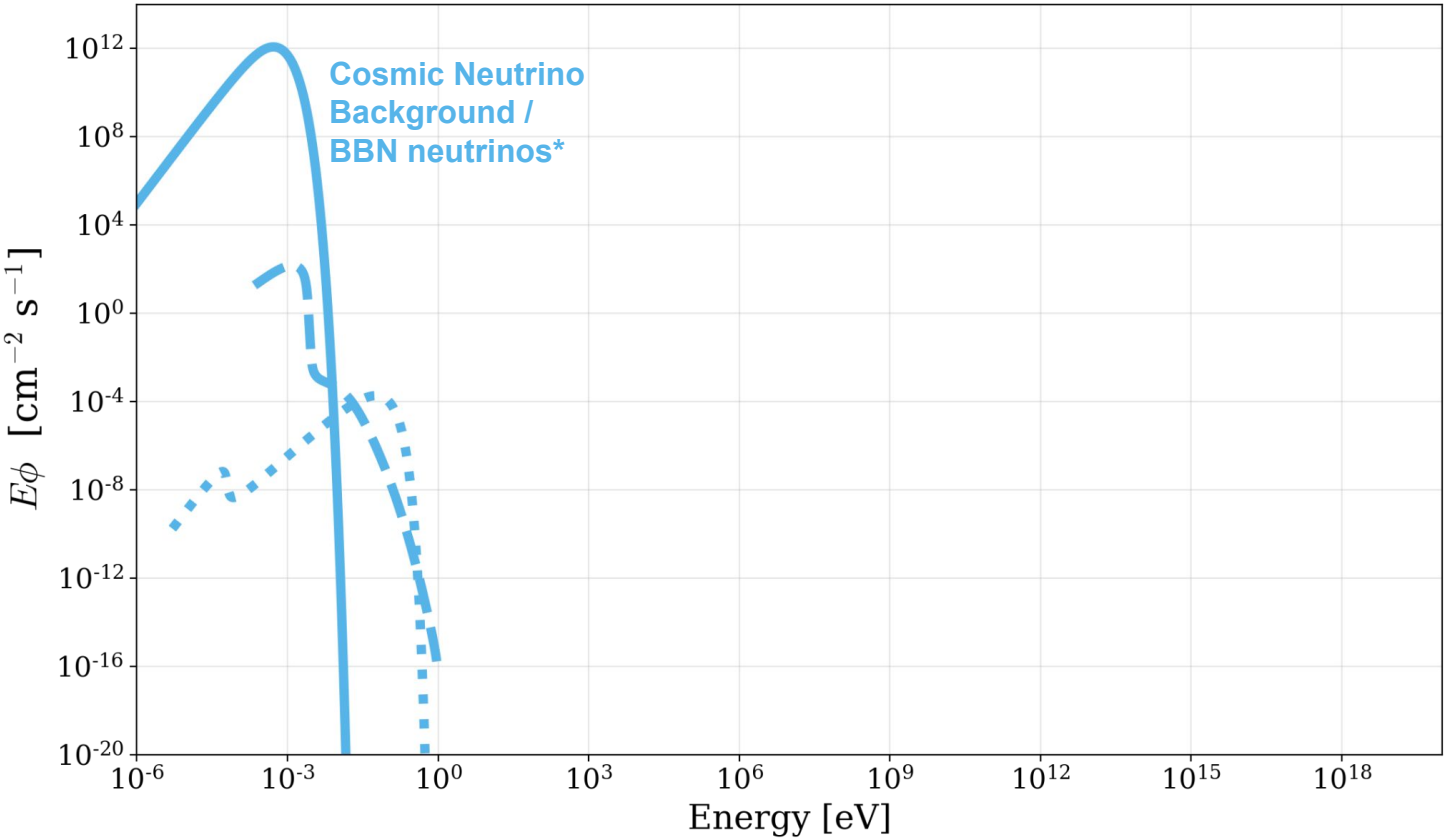
Cosmic Neutrino Spectrum



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Cosmic Neutrino Spectrum

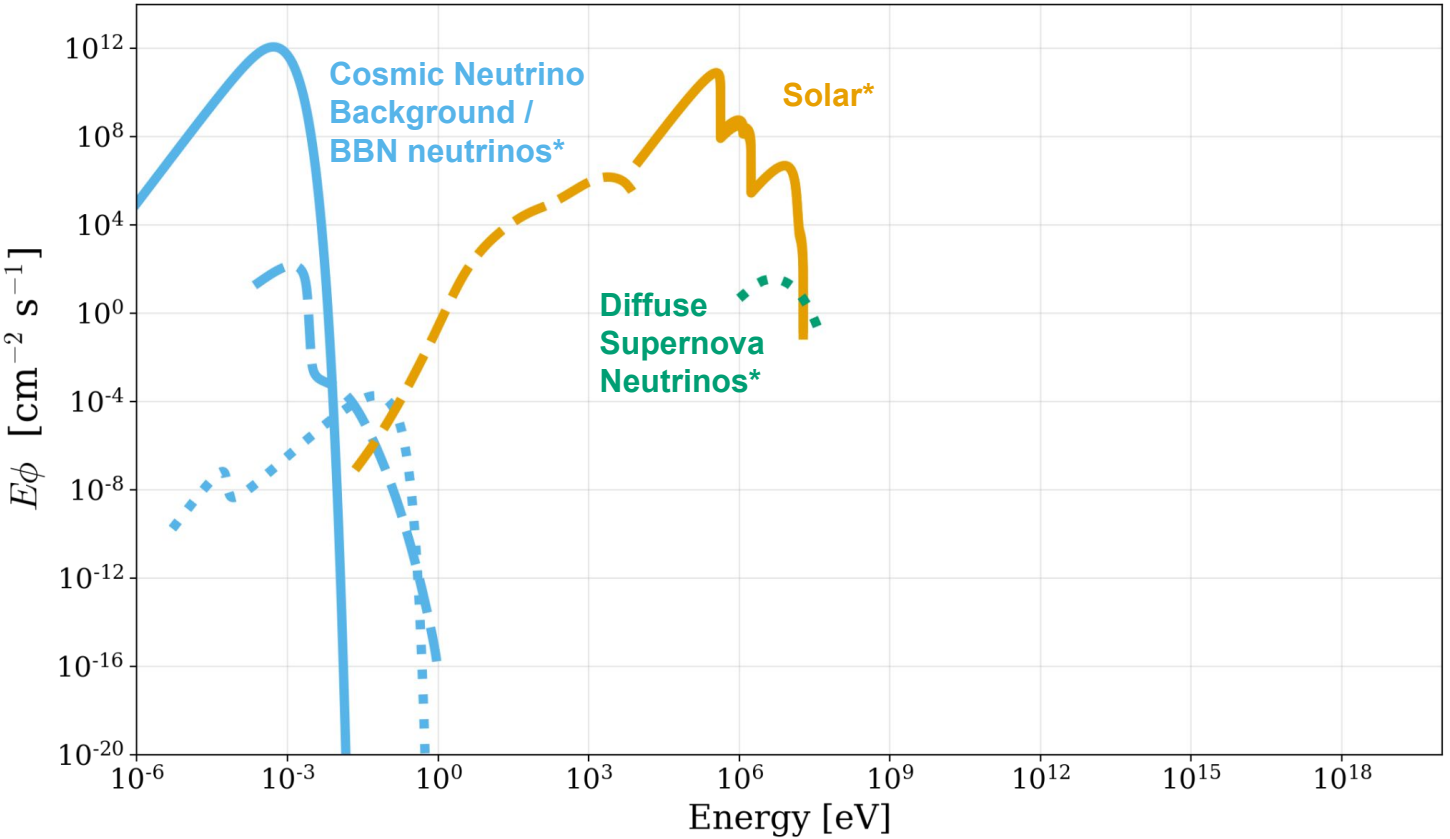
Vitagliano, Tamborra, Raffelt
Rev. Mod. Phys. **92**, 045006



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Cosmic Neutrino Spectrum

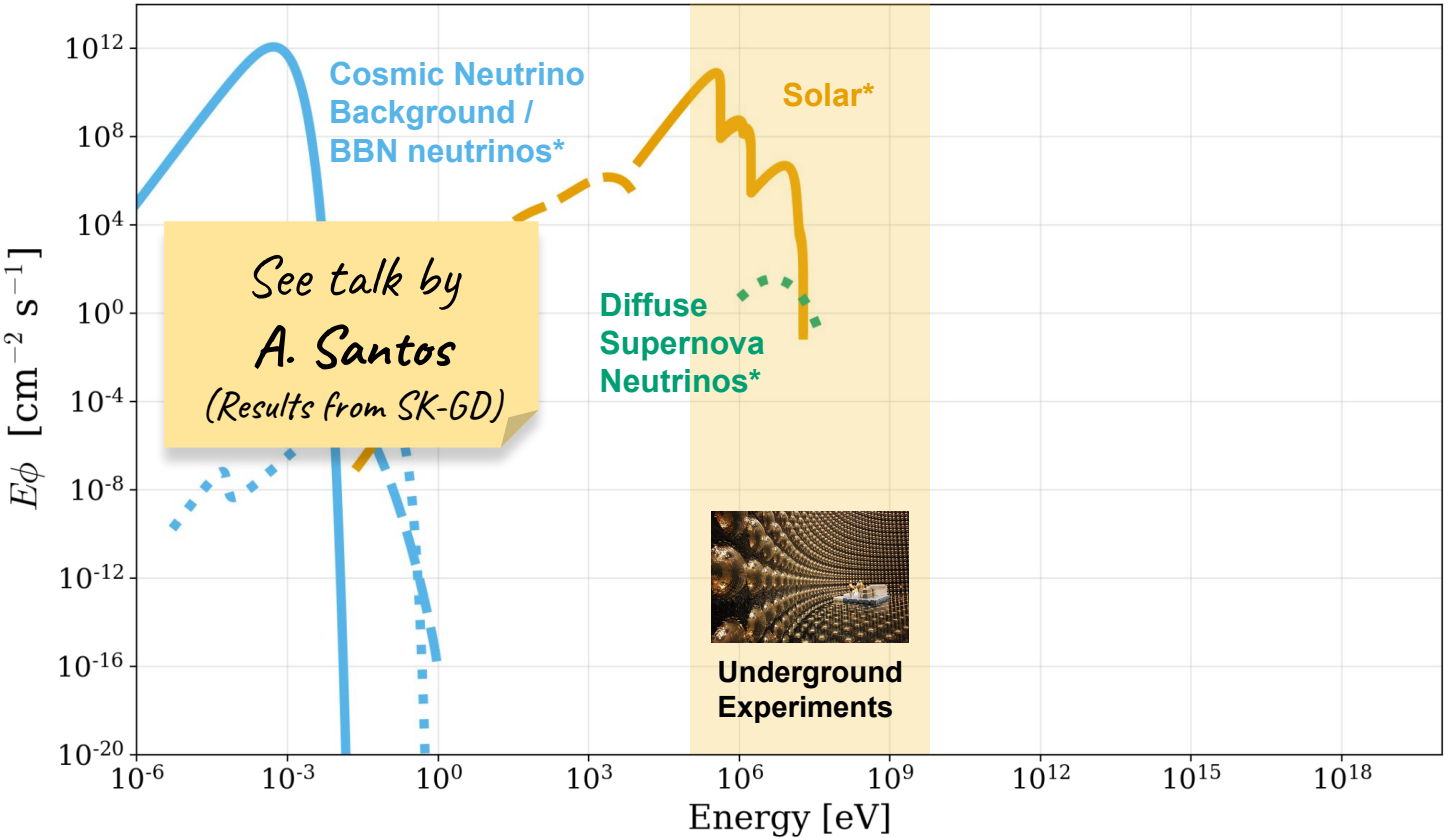
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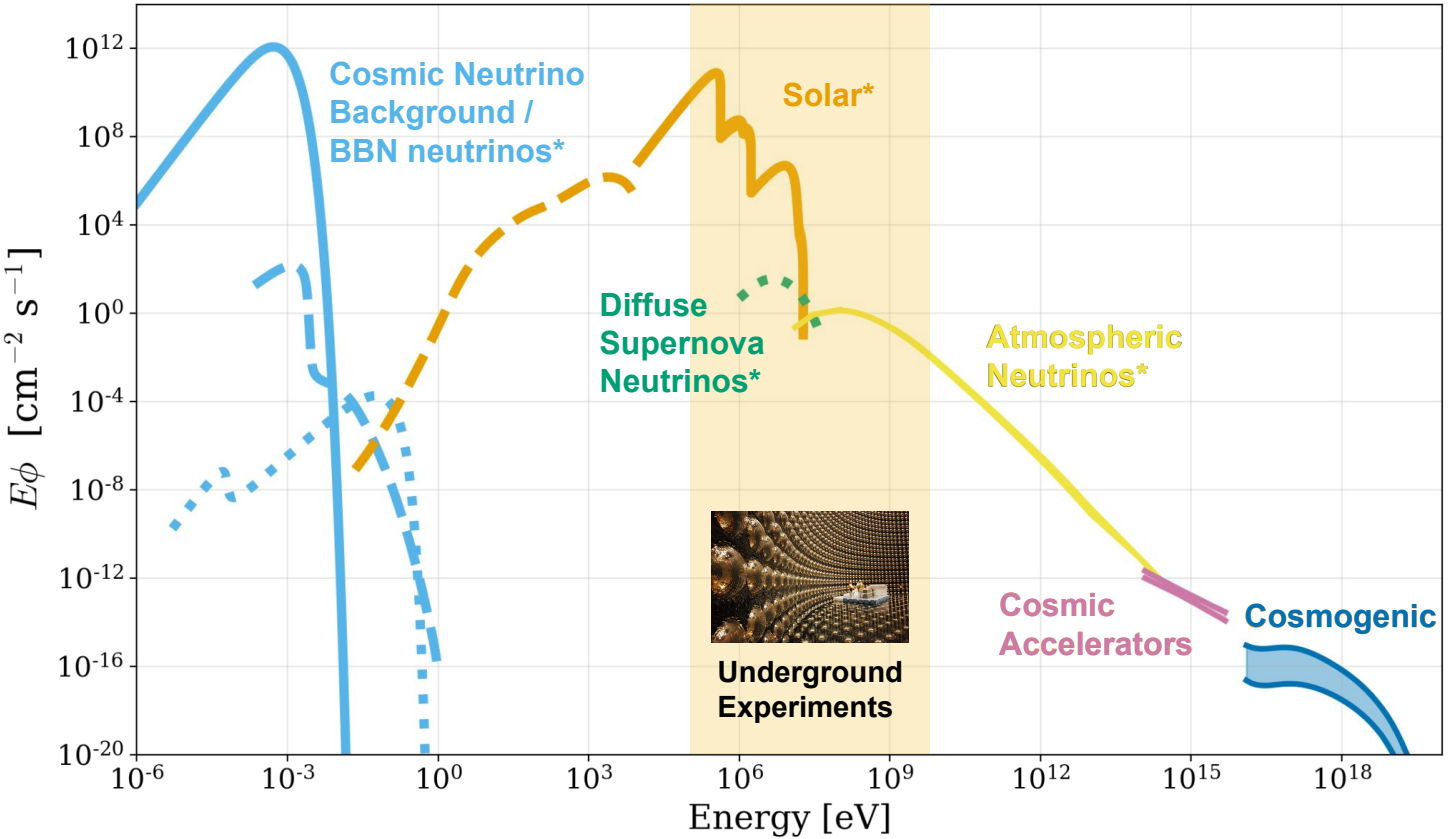
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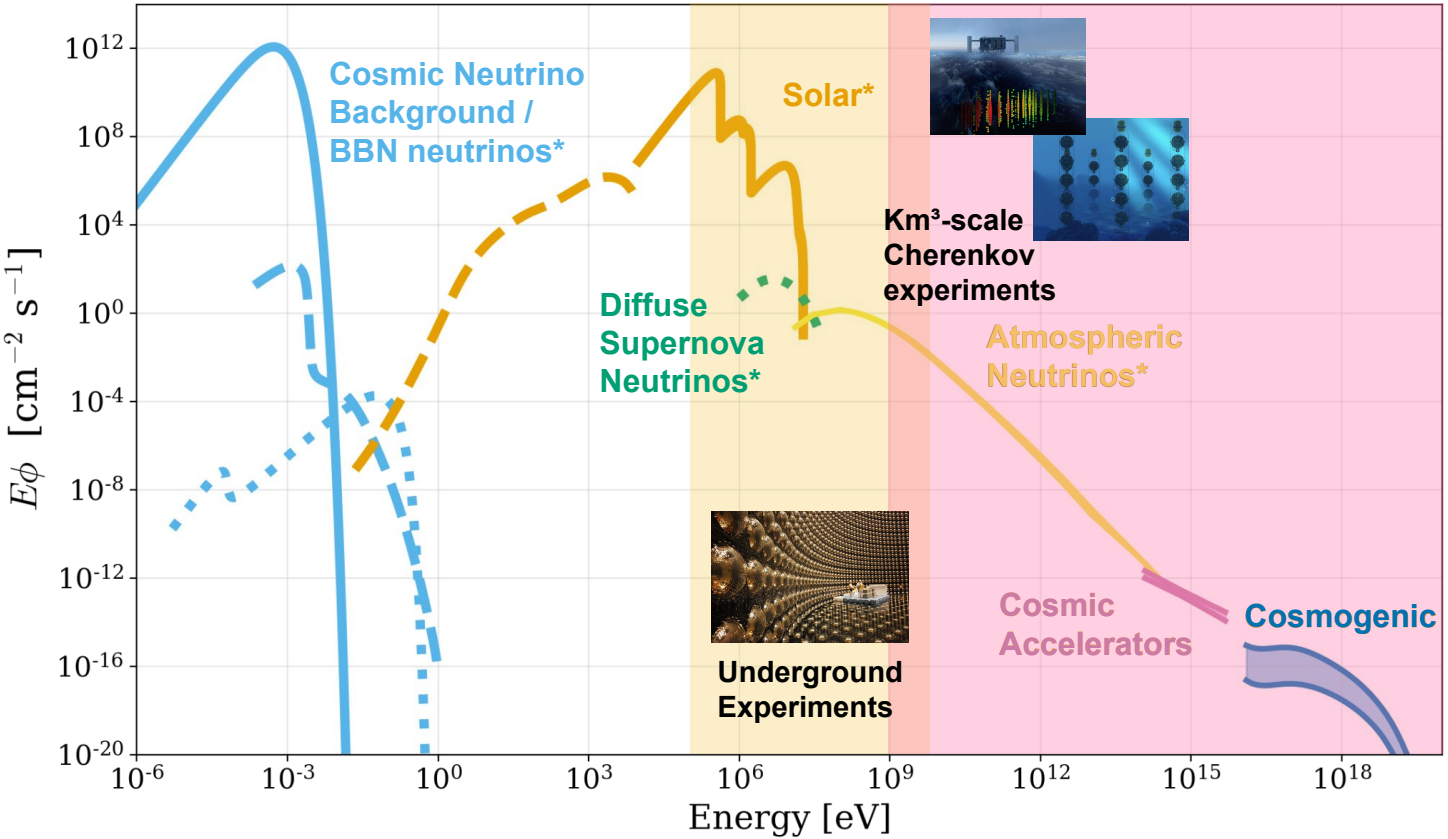
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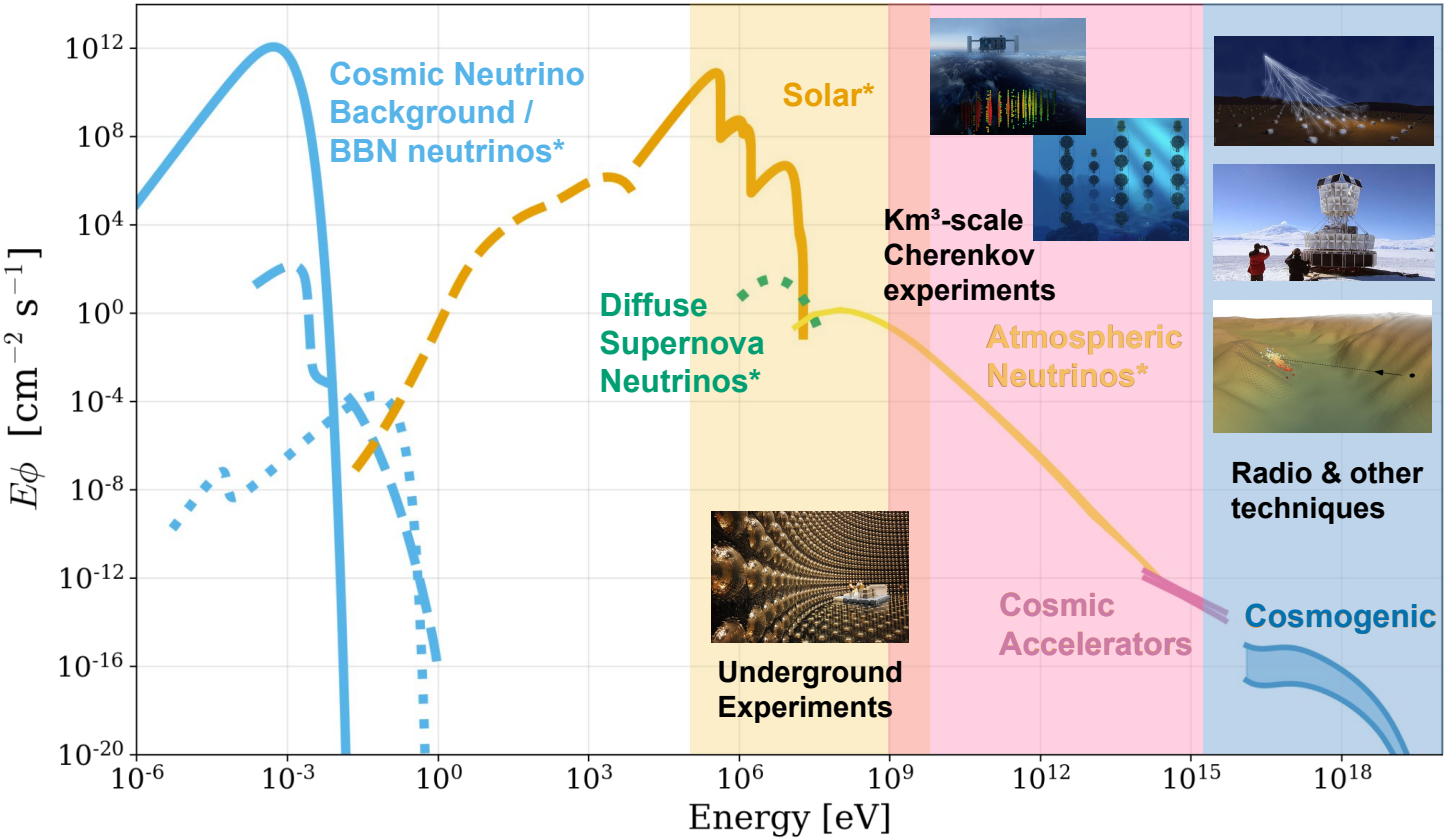
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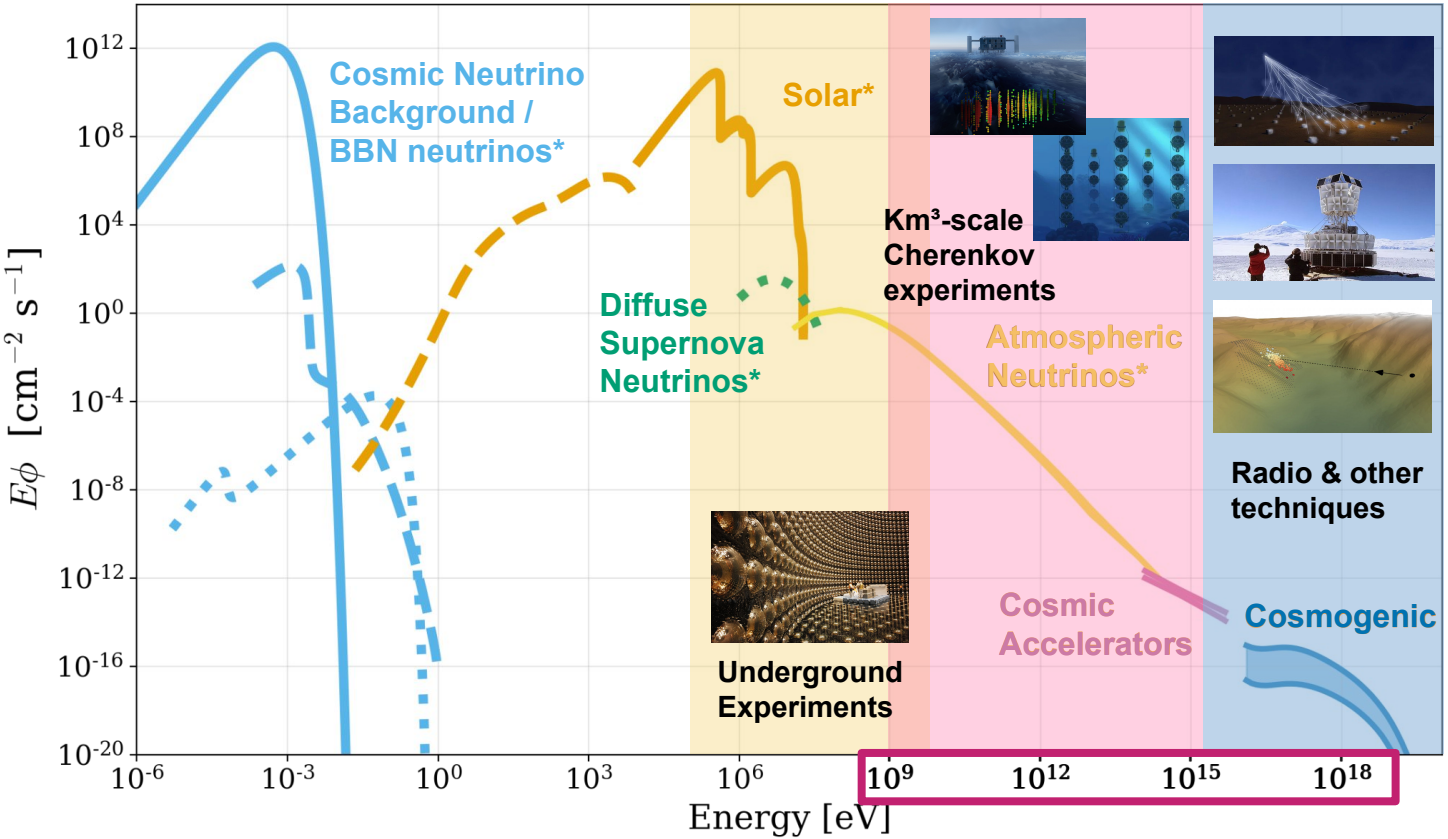
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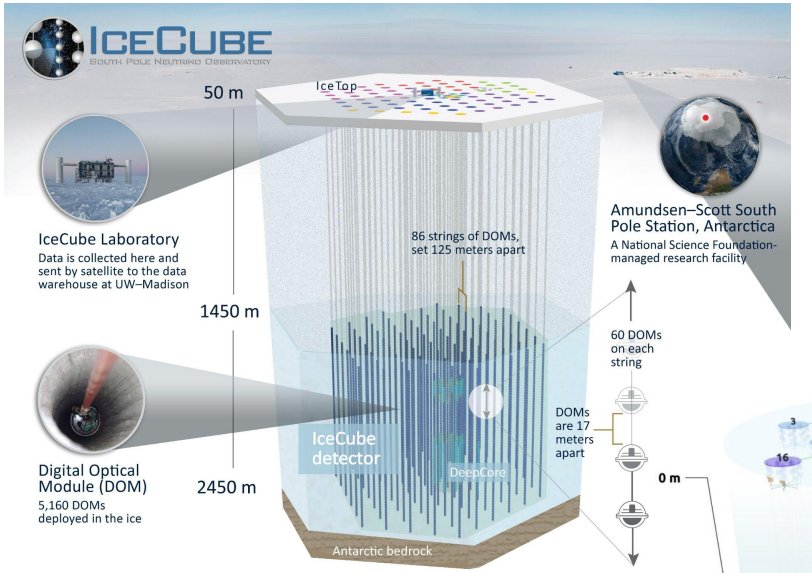
Cosmic Neutrino Spectrum

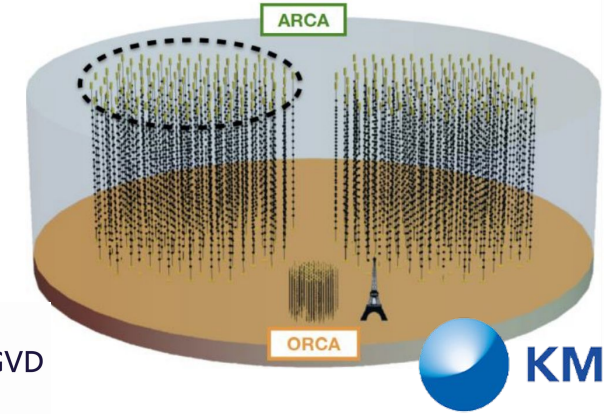
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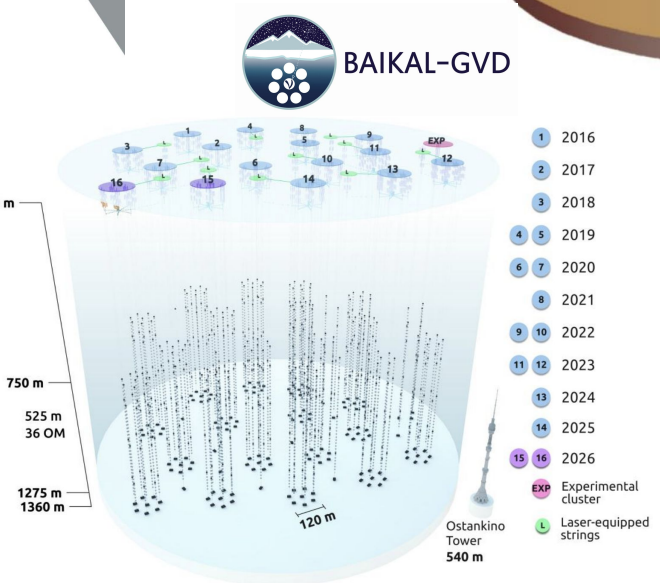


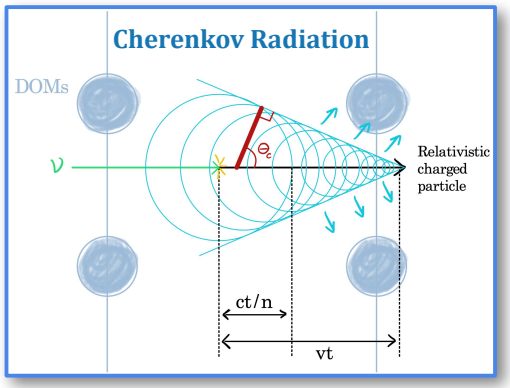
Km³-Scale Neutrino Observatories

Existing Water/Ice Cherenkov Observatories (>TeV)





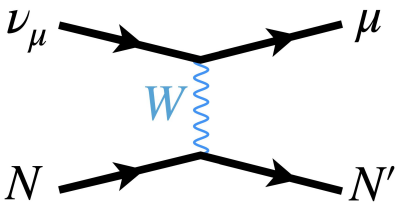


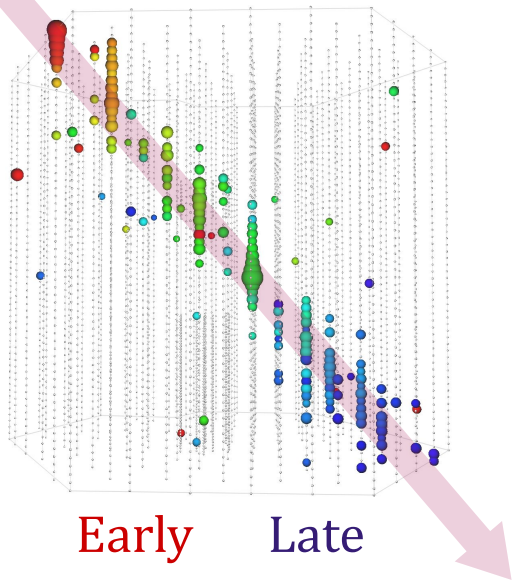


IceCube Event Topologies

Tracks

- Median angular resolution ~0.5°
- Vertex can be outside detector
- Difficult to estimate energy
- Categorized into through-going, starting, and stopping

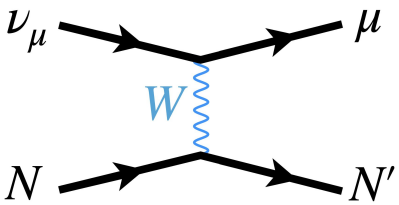


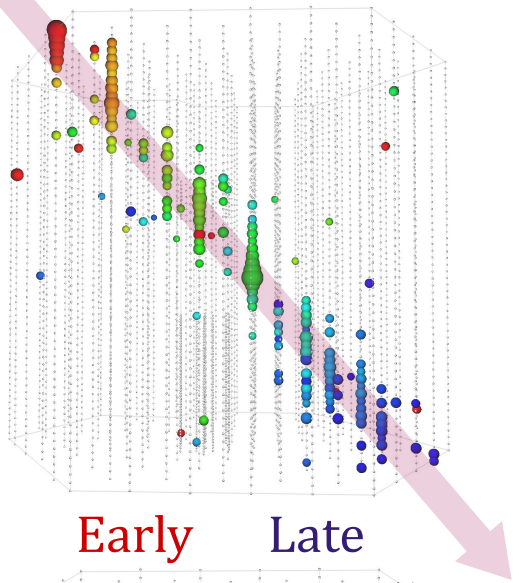


IceCube Event Topologies

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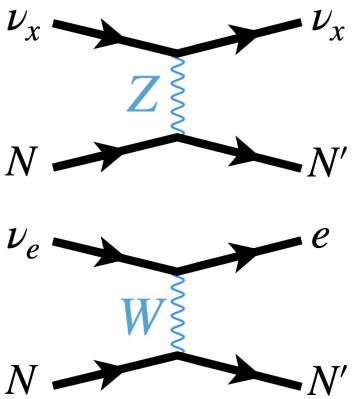
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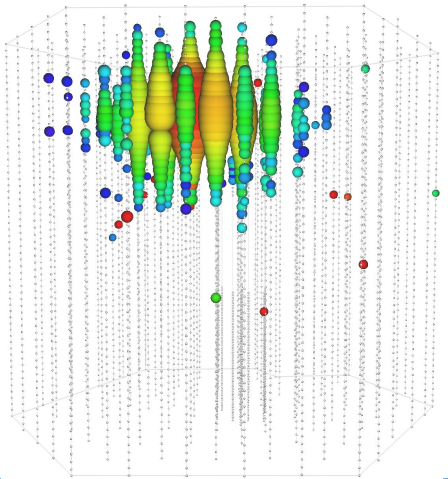




Cascades

- Median angular resolution ~8° at E > 100 TeV
- Vertex in or near detector
- Better energy resolution

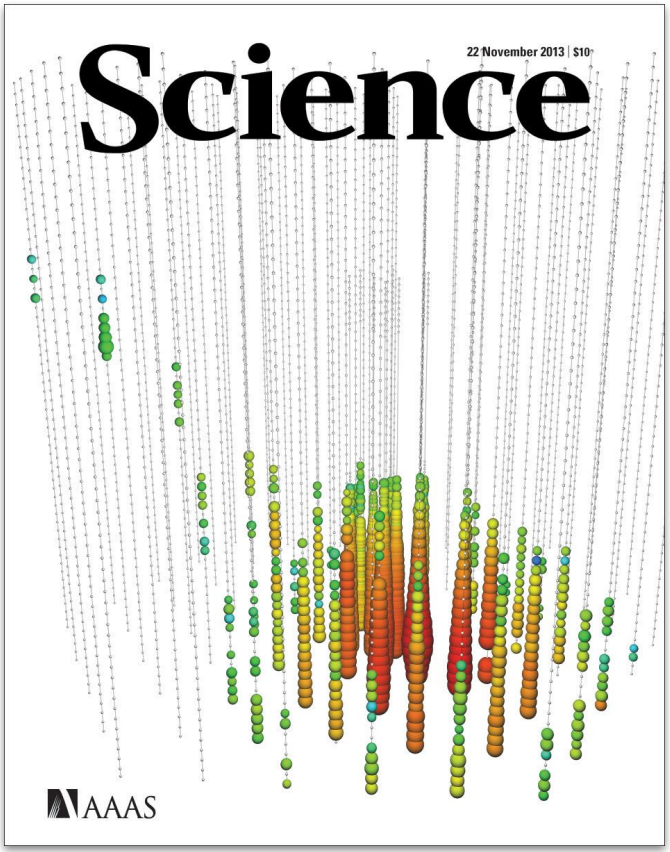




First Evidence of Astrophysical Neutrinos!

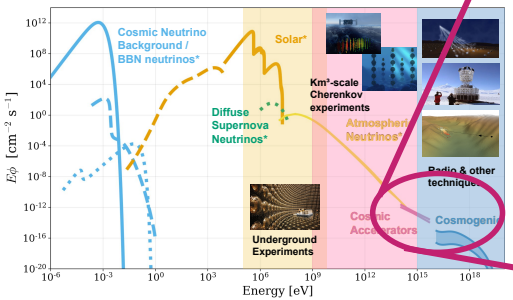
- IceCube announced first observation of high-energy astrophysical neutrino flux in 2013 (>4σ)
  - ***Nobel Prize awarded to IceCube's Francis Halzen in 2026!***

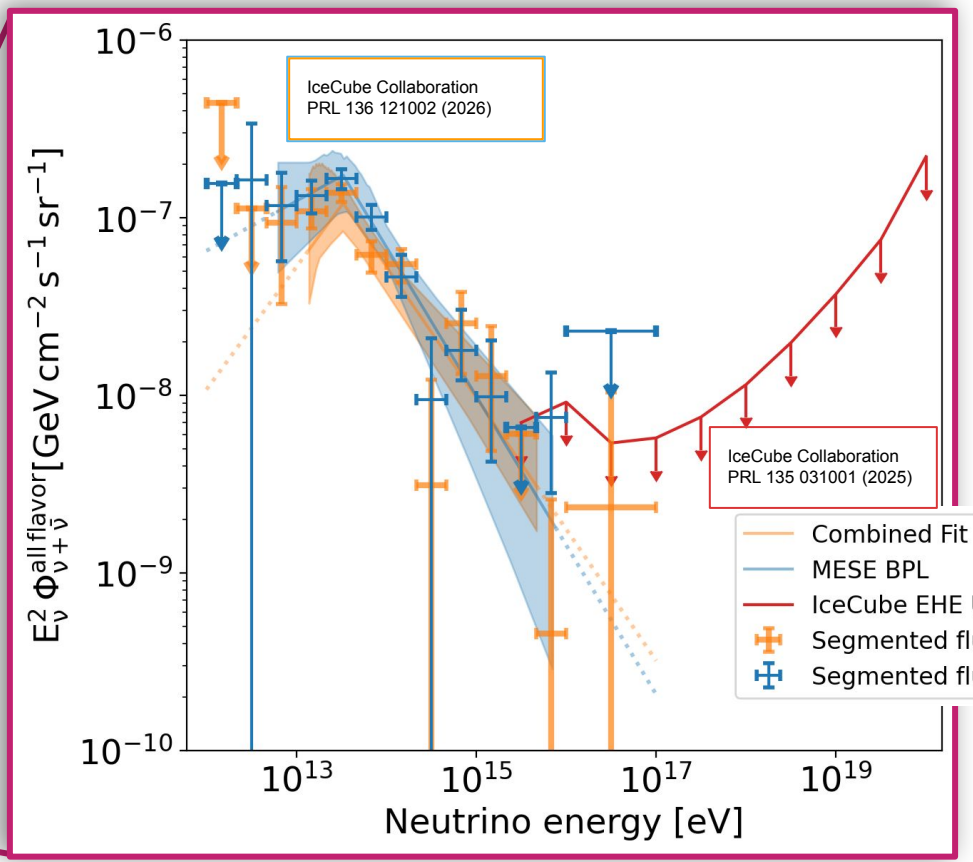
- Most sources of these neutrinos are still unknown...

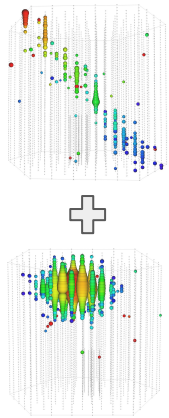


Astrophysical Neutrino Spectrum (TeV - PeV)

- Recent evidence by IceCube shows that ν spectrum likely follows a **broken-power law (BPL)**

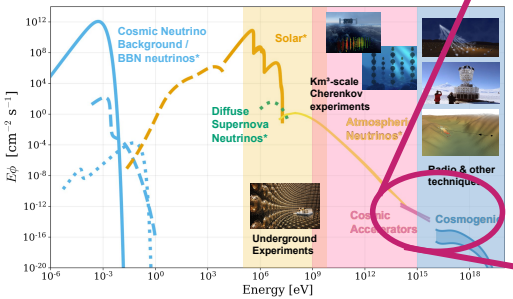


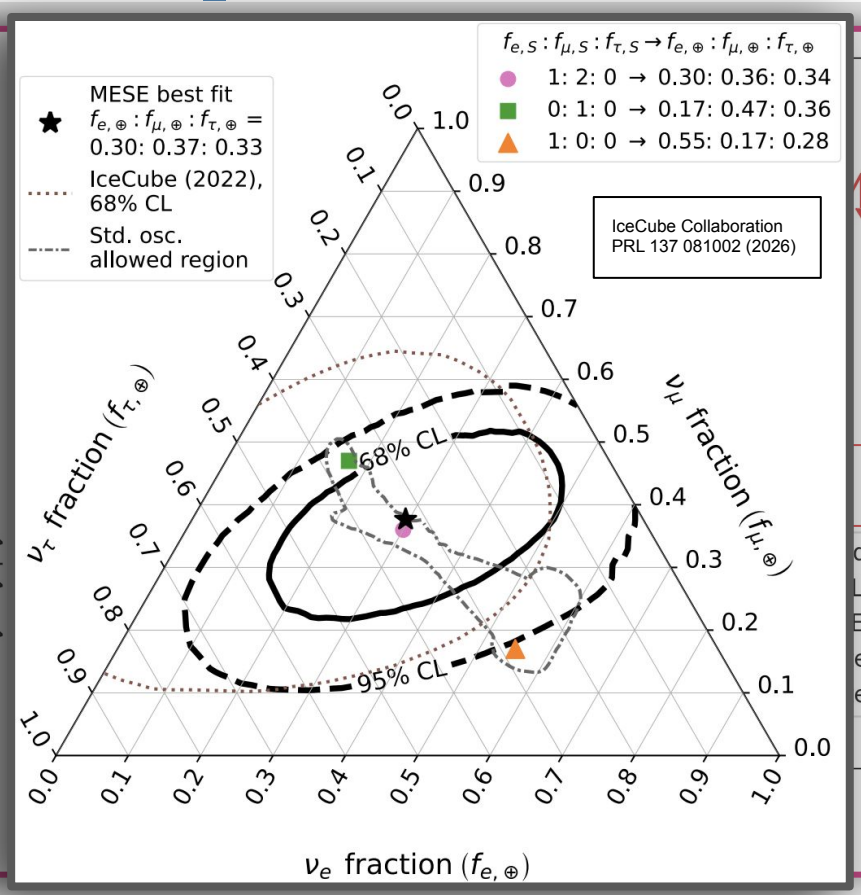


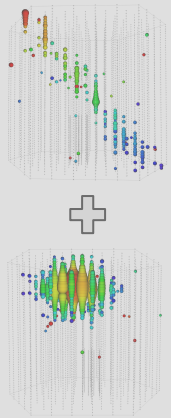


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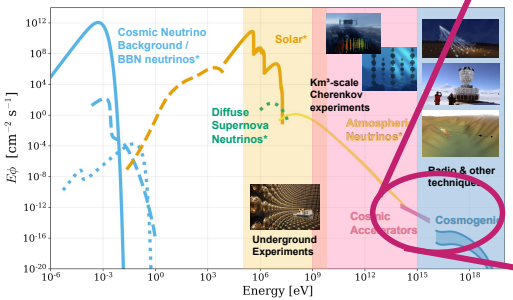


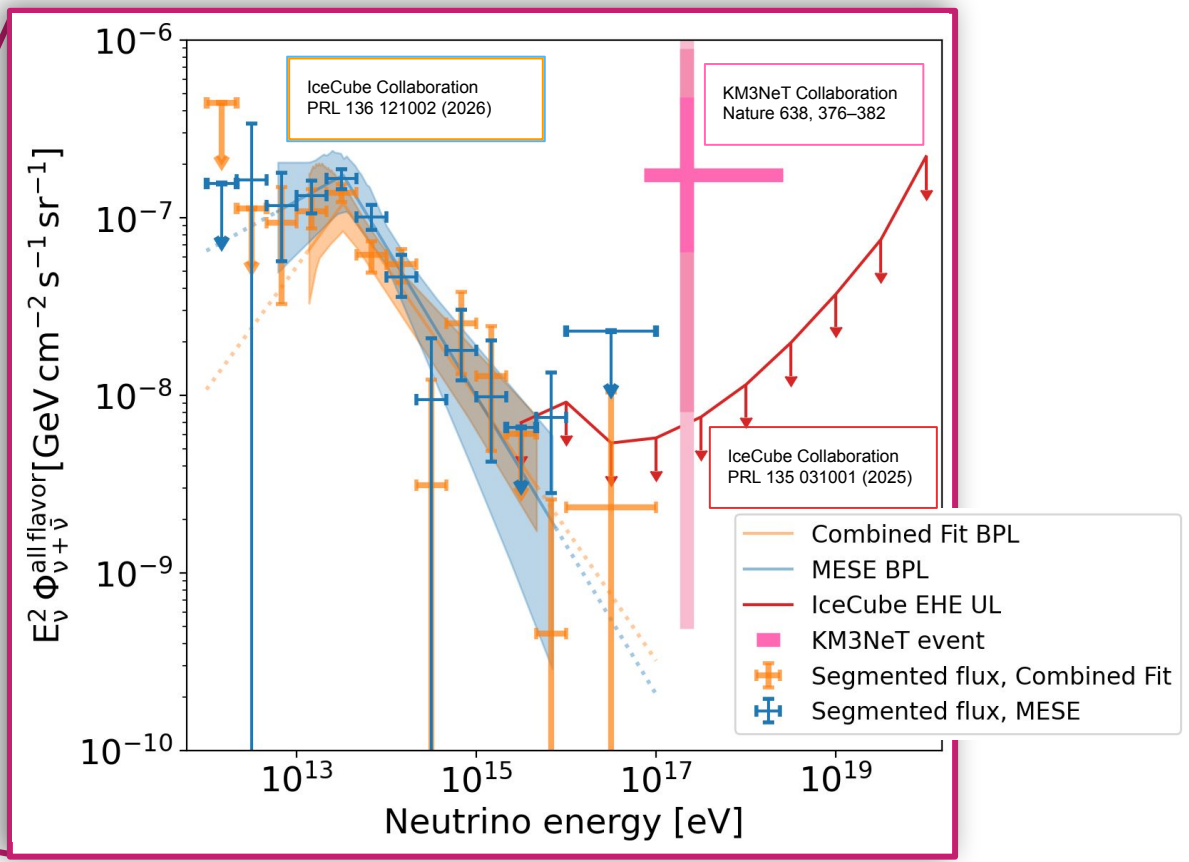


d Fit BPL
L
EHE UL
ed flux, Combined Fit
ed flux, MESE

Astrophysical Neutrino Spectrum (TeV - PeV)

- Recent evidence by IceCube shows that ν spectrum likely follows a **broken-power law (BPL)**
- Good agreement w/ charged π-decay & disfavors pure neutron β decay at 4σ
- KM3NeT EHE event in 2.9σ tension with IceCube data

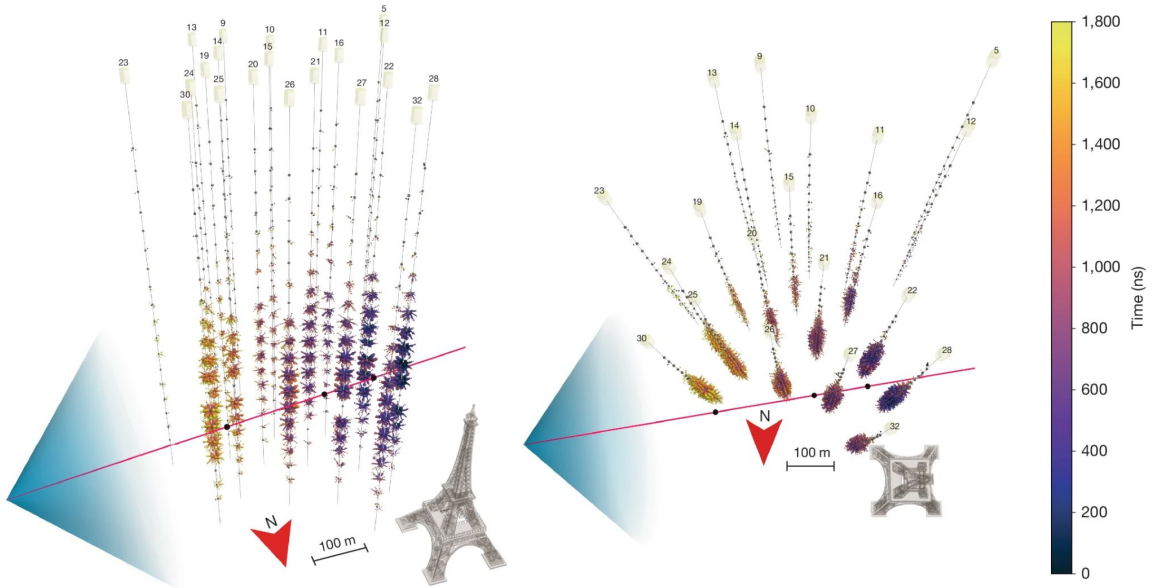




Highest energy neutrino ever reported…

- Detected Feb. 13, 2023 in ARCA detector
  - ➢ Only ~10% planned lines installed and operating at time of detection

- $E\nu = 220^{+570}_{-100}$ PeV

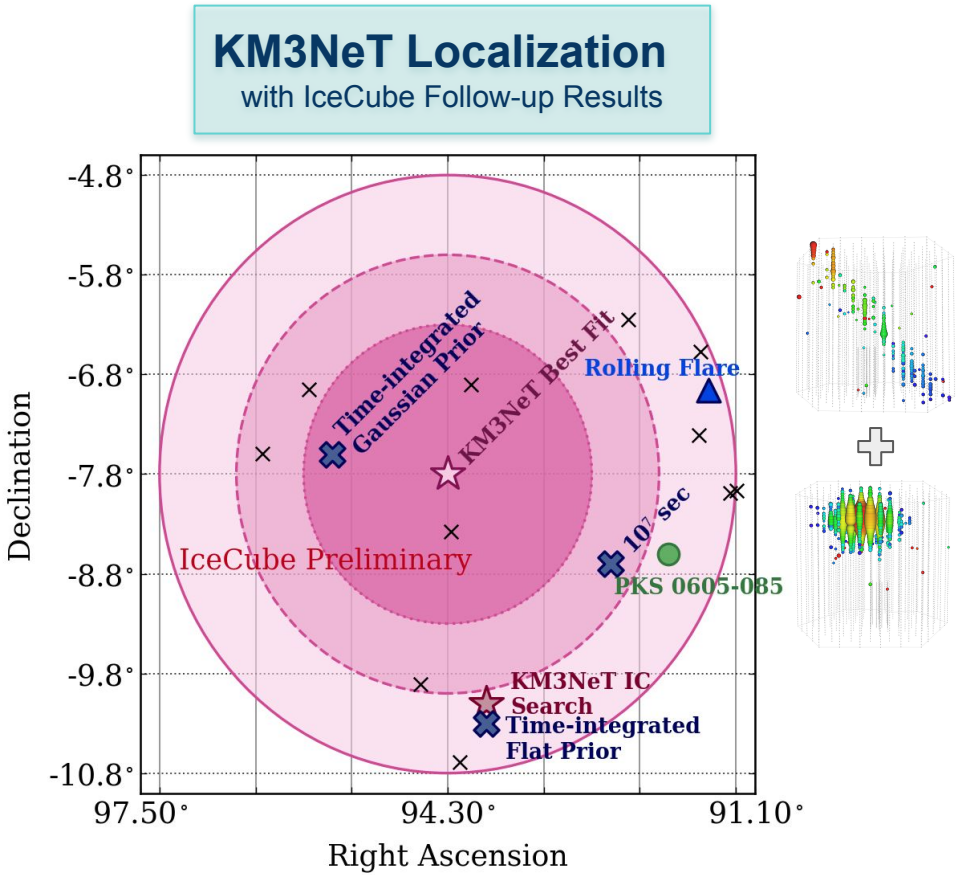


The KM3NeT Collaboration *Nature* **638**, 376–382

Highest energy neutrino ever reported...

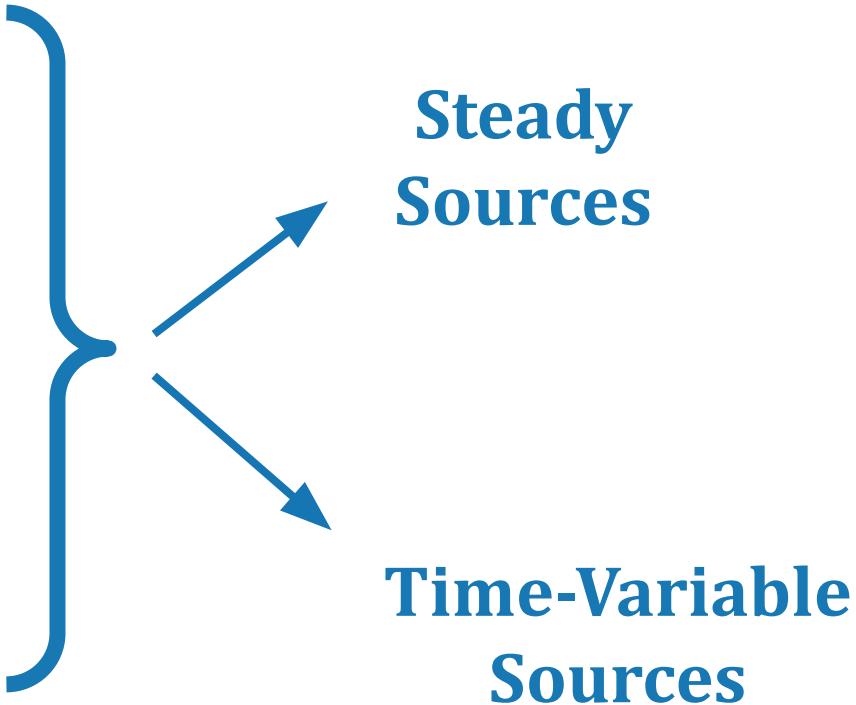
IceCube Collaboration
arXiv: 2609.10931

- No clear origin
  - No GRBs, supernovae, or TDEs have been identified in 99% confidence region
  - 12 nearby blazars but no temporal association
- IceCube follow-up
  - ***All follow-up results consistent with background expectations***
- Many hypotheses have been suggested
  - Cosmogenic neutrino
  - Primordial Black Hole
  - Beyond the standard model
  - …and more!

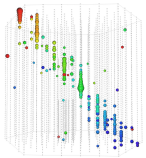


Recent High-Energy Neutrino Source Search Results

- Active Galactic Nuclei (AGN)
  - Blazars
  - Seyferts
  - X-Ray Bright
- Supernova Remnants (SNRs) & Supernovae
- Gamma-ray Bursts (GRBs)
- Galactic plane

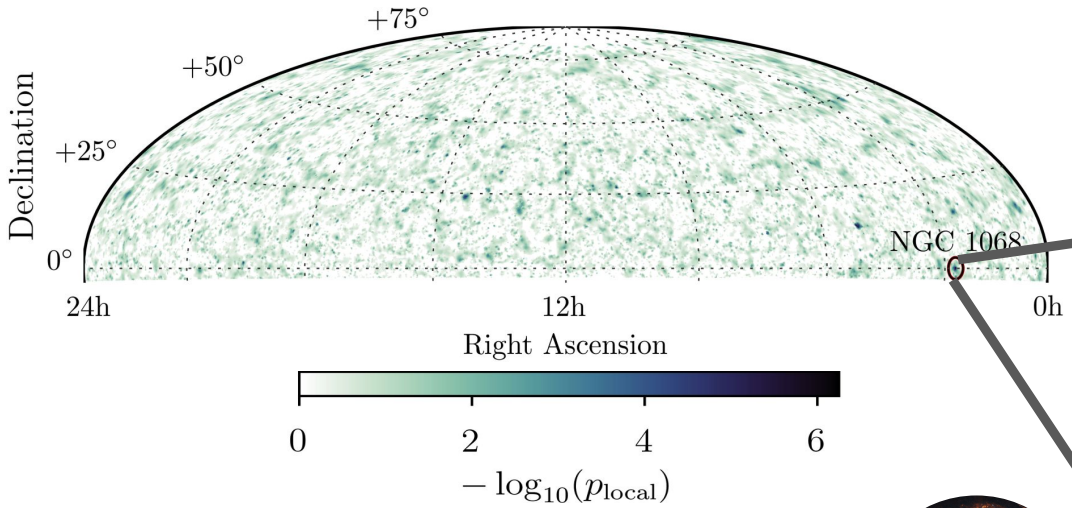


Recent **Steady Source** Search Results



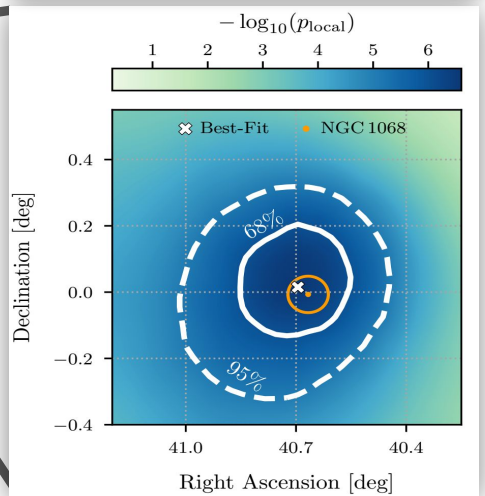
IceCube Collaboration
ApJL 1000 (2026) L26

Up-going ν_μ Events (Tracks)



Identification of known seyfert galaxy NGC 1068 as likely neutrino source!

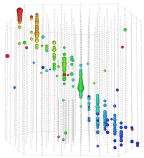
Global Significance: **4.0σ**

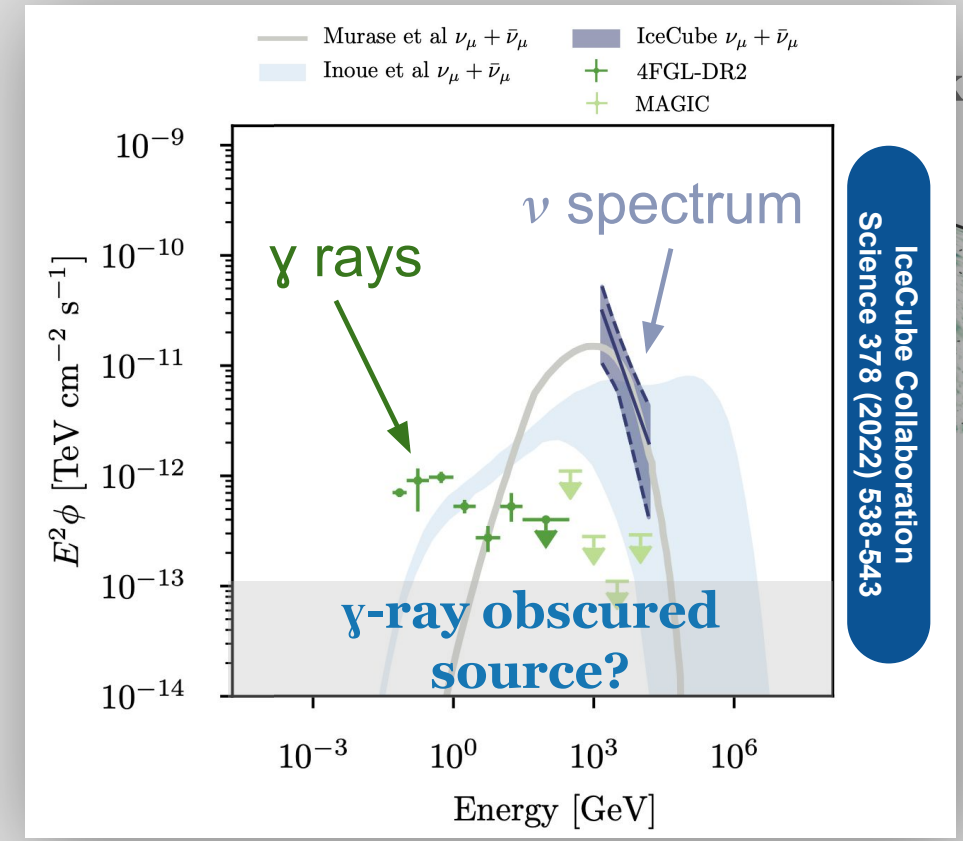


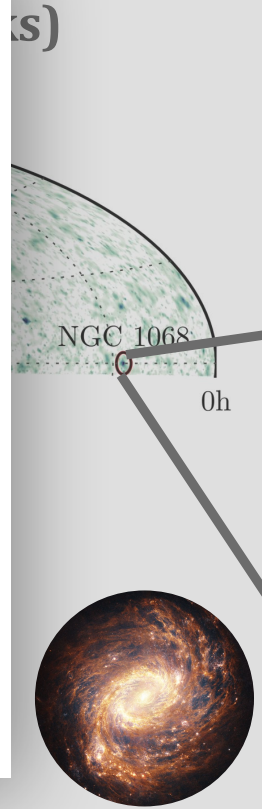


* Galaxy Image Credit: NASA

Recent **Steady Source** Search Results

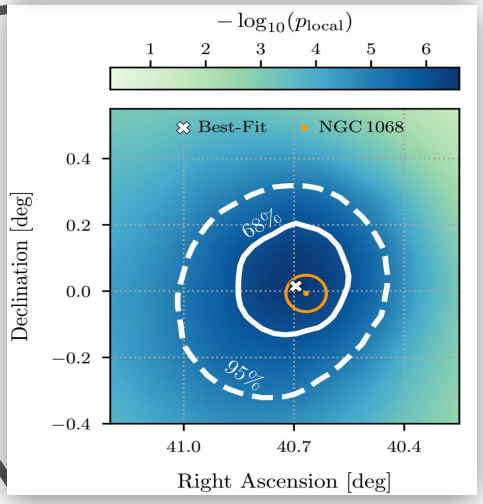






Identification of known seyfert galaxy NGC 1068 as likely neutrino source!

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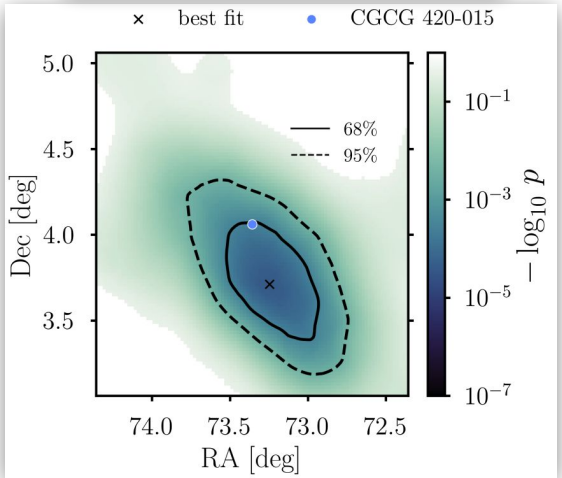


* Galaxy Image Credit: NASA

Recent **Steady Source** Search Results

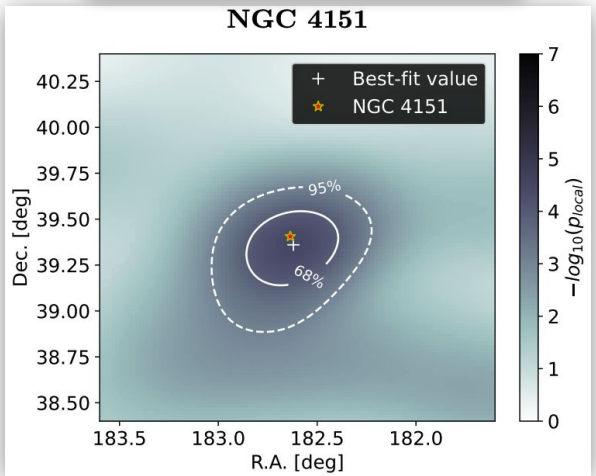


Global Significance: **2.5σ**





Global Significance: **2.9σ**

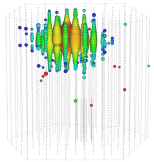


Study of **X-Ray bright seyferts** using up-going ν_μ (track) events builds on NGC 1068 result

IceCube Collaboration
ApJ 988 (2025) 141

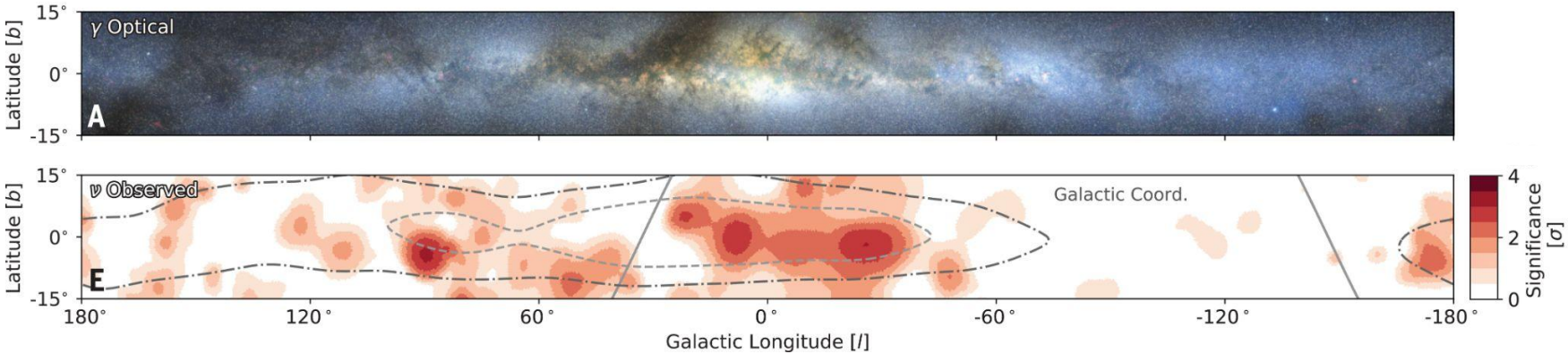
* Galaxy Image Credit: NASA

Recent **Steady Source** Search Results



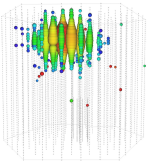
IceCube Collaboration
Science 380 (2023) 1338-1343

★ 2023: Observation of ν from the Galactic Plane using 10 years of **cascade** data!



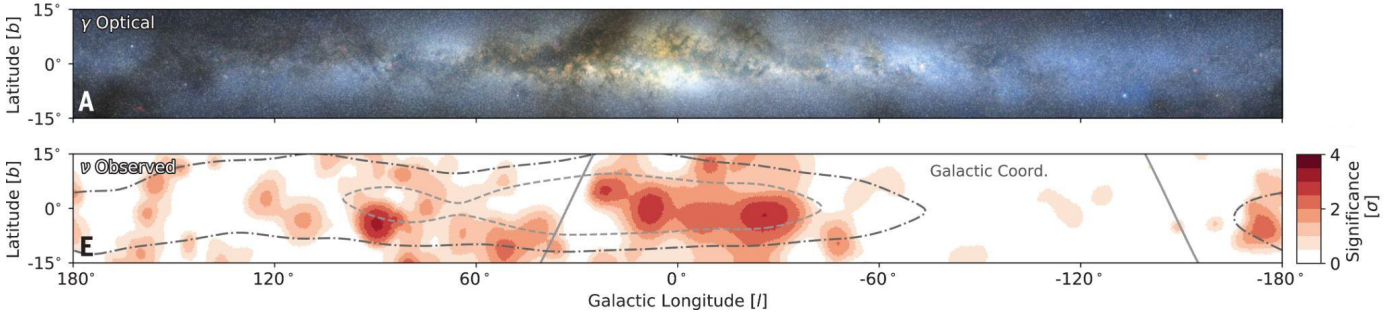
Galactic Plane Global Significance **4.5σ**

Recent **Steady Source** Search Results



IceCube Collaboration
Science 380 (2023) 1338-1343

★ 2023: Observation of ν from the Galactic Plane using 10 years of **cascade** data!



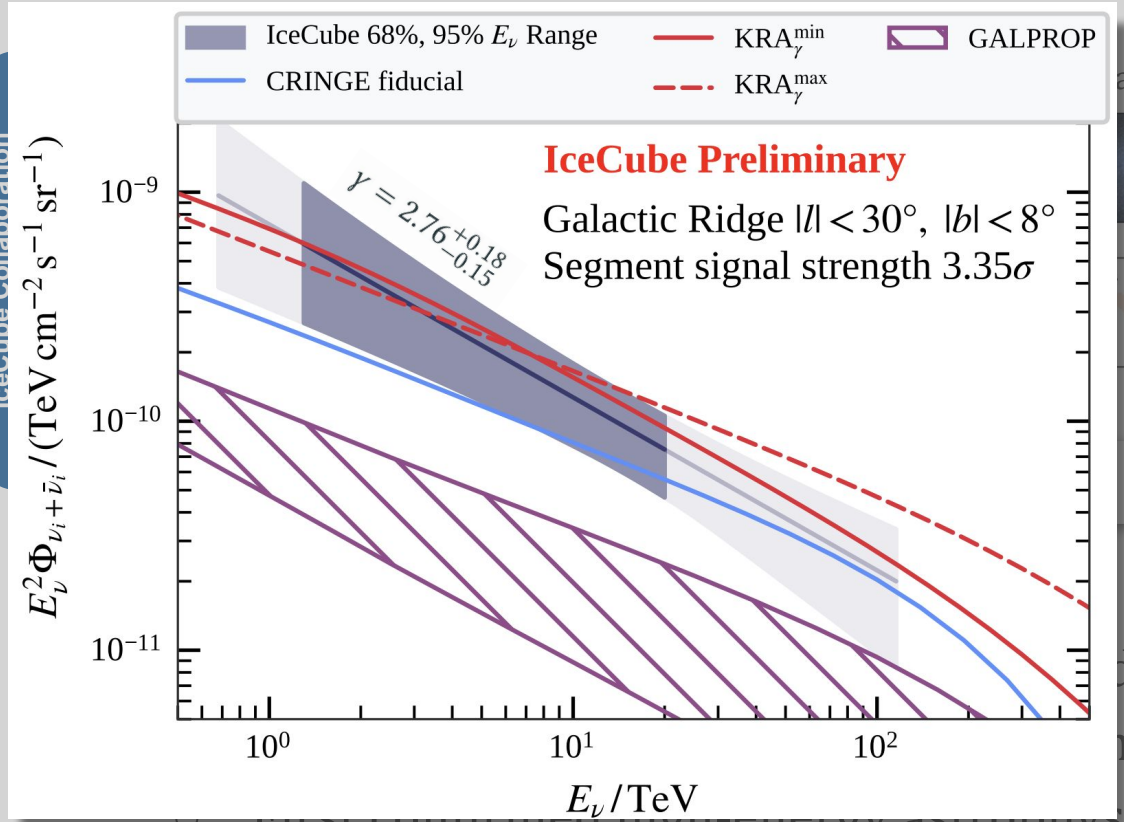
Galactic Plane Global Significance: **4.5σ**

★ Recent update:

Addition of 2 more years of data resulted in Local Significance ~ **5.7σ**

- Expected growth due to steady neutrino emission
- First confirmed high-energy astrophysical neutrino source!

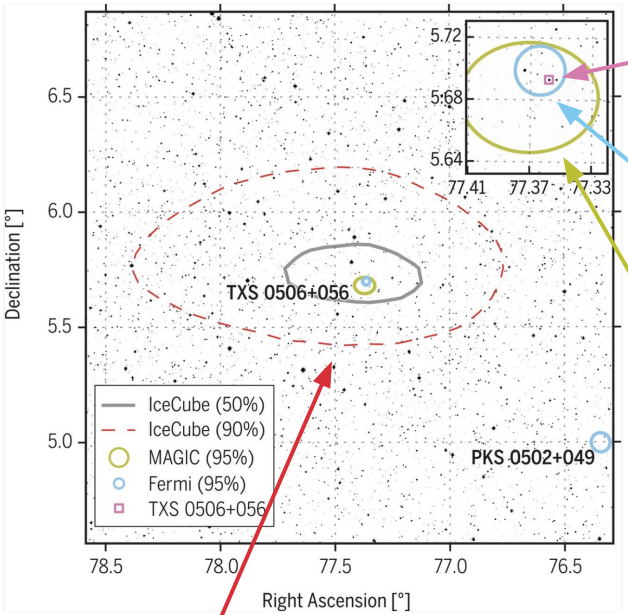
Recent **Steady Source** Search Results



Can start to make measurements of different parts of the Galactic Plane!

e.g. how steeply the neutrino flux falls with energy at the inner part of the GP

Recent **Time-Variable** Search Results



optical position

Fermi ɣ-ray detection

MAGIC telescope ɣ-ray detection

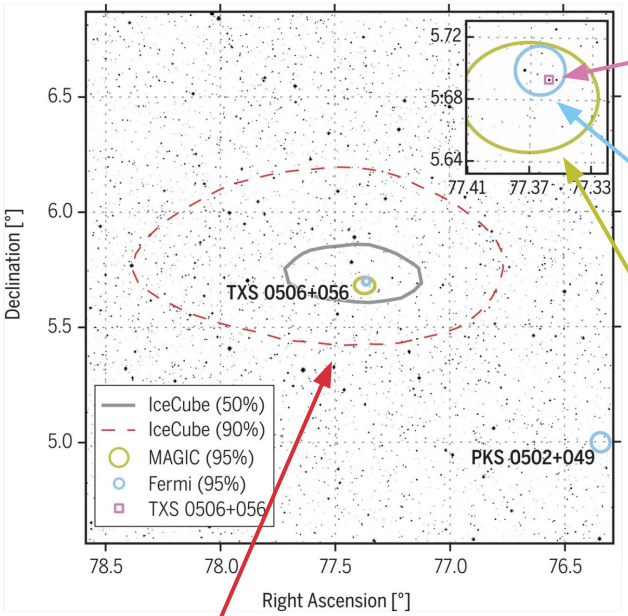
IceCube Event IC170922A (90% CL Uncertainty)

IceCube Collaboration
Science 361 (2018) eaat1378

Blazar TXS 0506+056

★ High energy neutrino event in 2017 coincident with TXS flare (3σ)

Recent **Time-Variable** Search Results



optical position

Fermi ɣ-ray detection

MAGIC telescope ɣ-ray detection

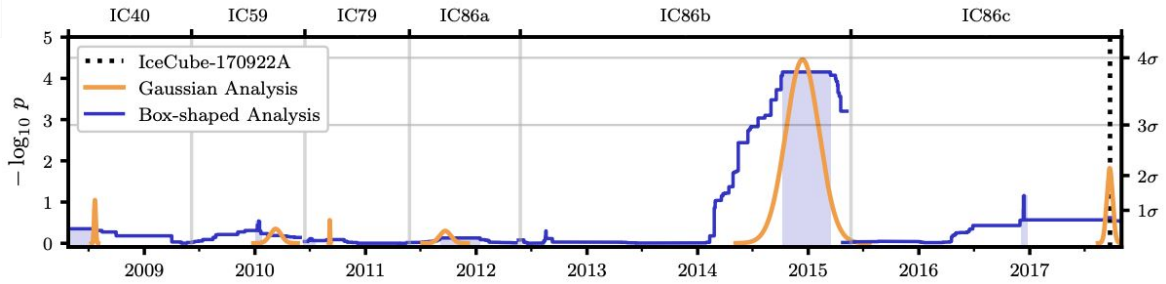
IceCube Event IC170922A (90% CL Uncertainty)

IceCube Collaboration Science 361 (2018) eaat1378

Blazar TXS 0506+056

- ★ High energy neutrino event in 2017 coincident with TXS flare (3σ)
- ★ Archival neutrino flare also found at 3σ

IceCube Collaboration Science 361 (2018) 147-151

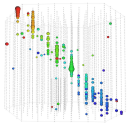


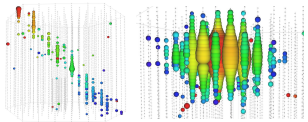
Newest IceCube analyses have started combining all-flavor CC and NC neutrino events

The simultaneous fit of all-flavor CC and NC neutrino events improves sensitivity for source searches

Why this works: Predominant Background

- Cosmic rays interact with the atmosphere
  - Produces **atmospheric μ (*tracks*)**
  - Produces **atmospheric ν (*tracks or cascades*)**

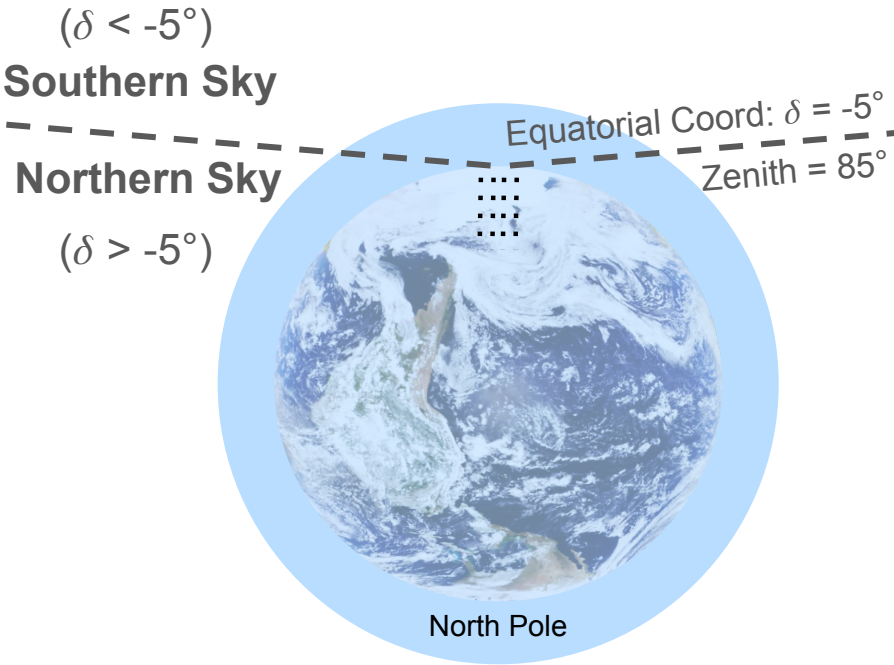




Atm. μ: ~ 10^{11} per year

Atm. ν: ~ 10^{5} per year

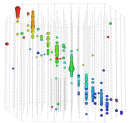
Astro. ν: ~100 per year

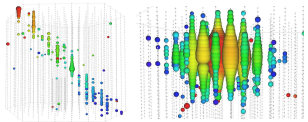


δ : *Equatorial Declination*

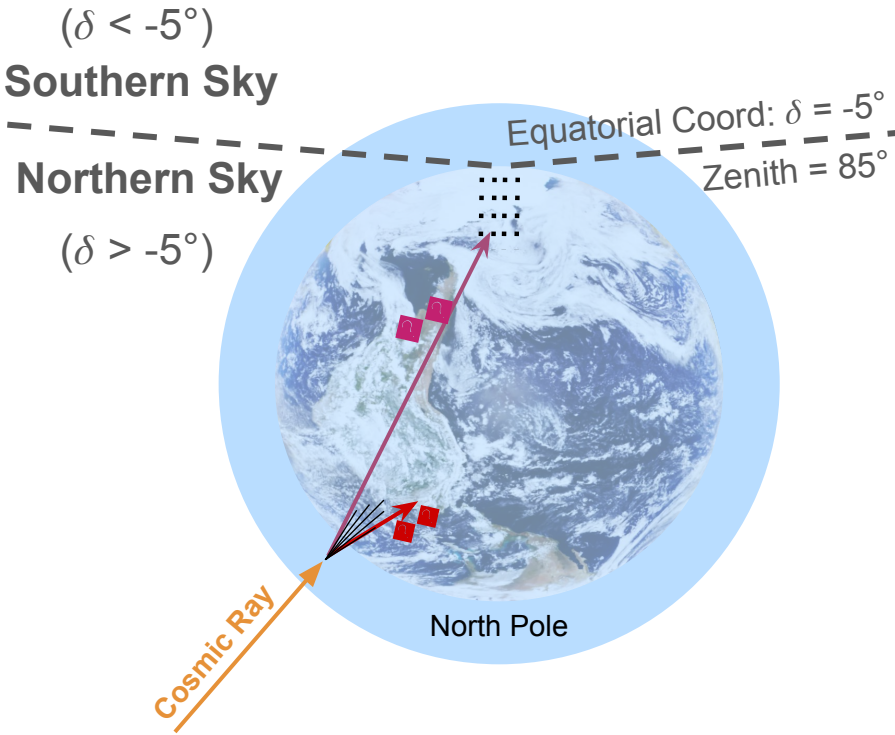
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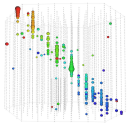
- **Earth absorbs almost all background μ from Northern Sky** (zenith > 85°)

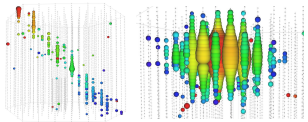


δ : *Equatorial Declination*

Why this works: Predominant Background

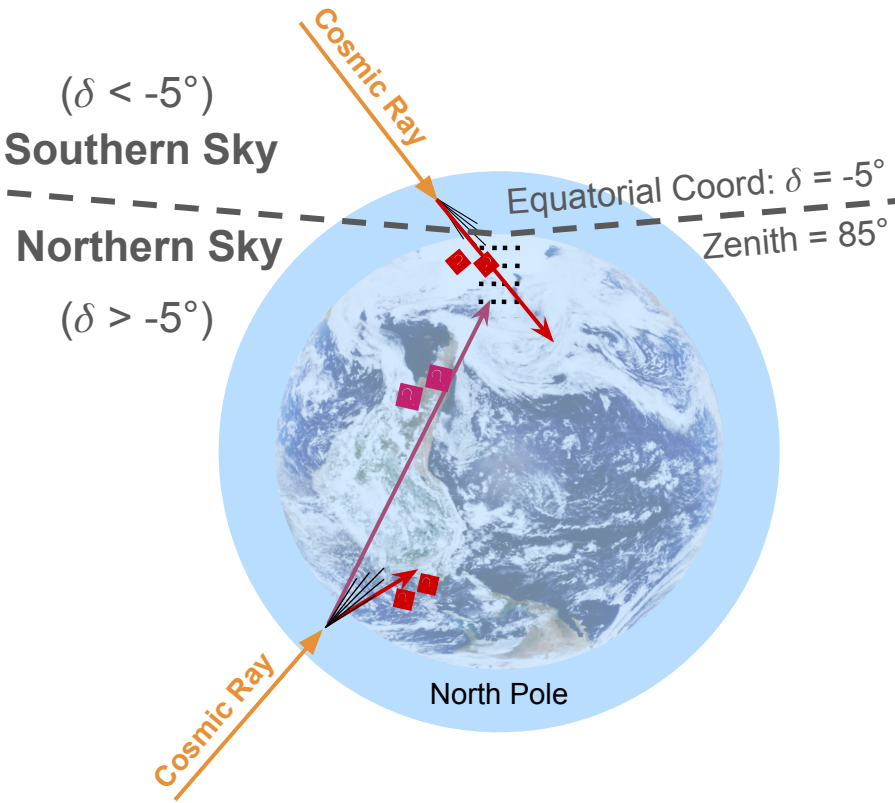
- Cosmic rays interact with the atmosphere
  - Produces **atmospheric μ (*tracks*)**
  - Produces **atmospheric ν (*tracks or cascades*)**





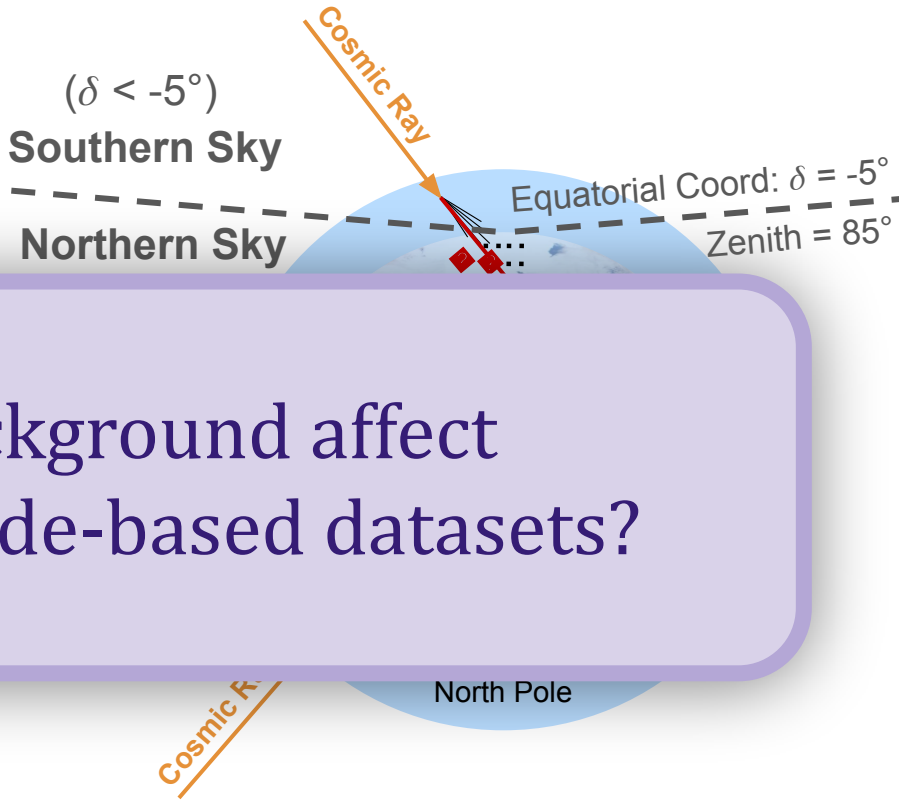
- **Earth absorbs almost all background μ from Northern Sky** (zenith > 85°)

- **Southern Sky** (zenith < 85°) **is filled with background μ (no Earth filter)**



δ : Equatorial Declination

Why this works: Predominant Background



- Cosmic rays interact with the atmosphere

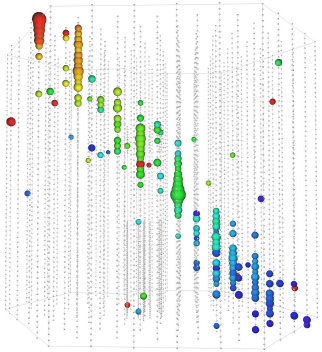
How does our background affect track-based and cascade-based datasets?

- **Southern Sky** (zenith < 85°) **is filled with background μ (no Earth filter)**

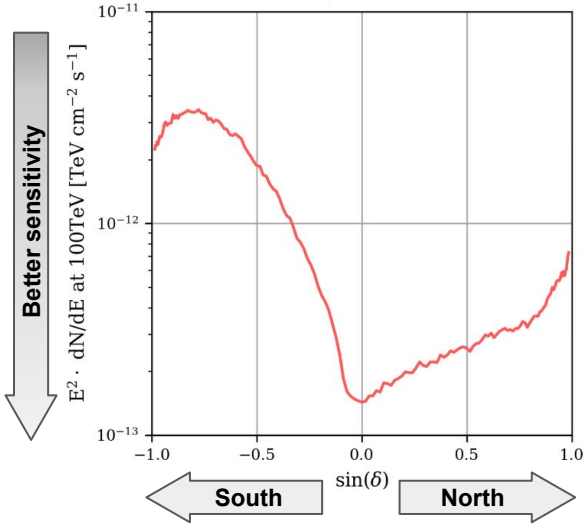
δ : *Equatorial Declination*

Background Effects on Datasets

Track-Based



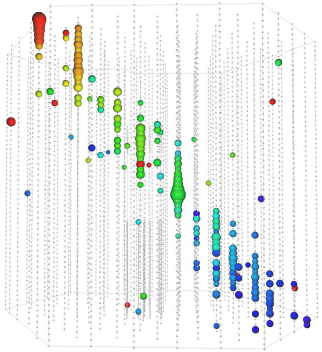
Southern Sky background μ require harsh low-energy cuts on Southern Sky track events



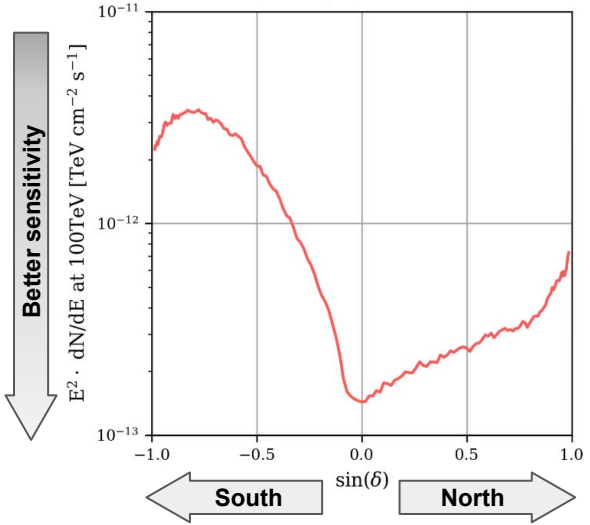
IceCube Collaboration ApJ 995 (2025) 11

Background Effects on Datasets

Track-Based

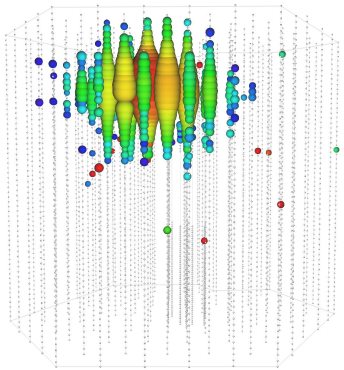


Southern Sky background μ require harsh low-energy cuts on Southern Sky track events

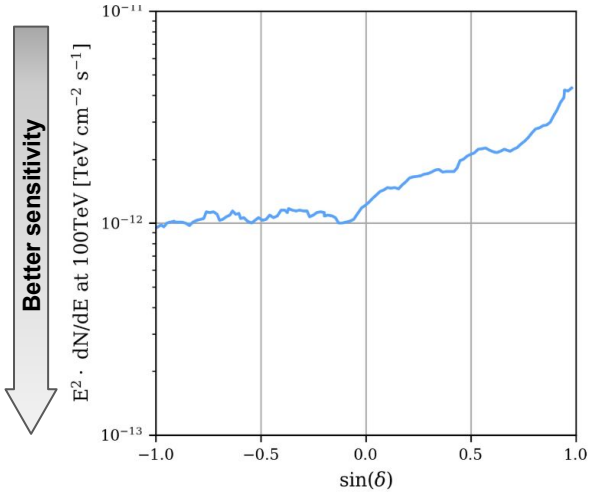


IceCube Collaboration ApJ 995 (2025) 11

Cascade-Based

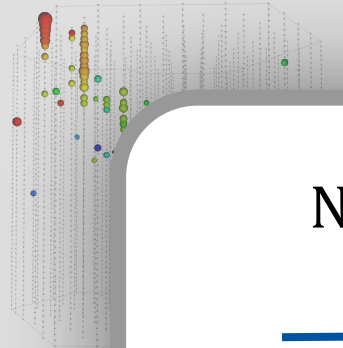


Since μ do not appear as cascades, no low-energy cuts necessary in Southern Sky



Background Effects on Datasets

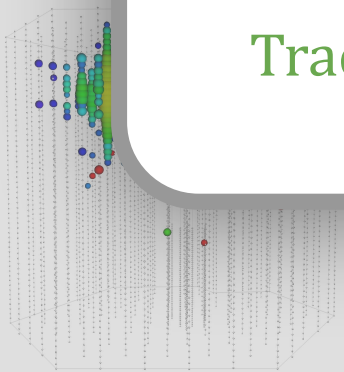
Track-Based



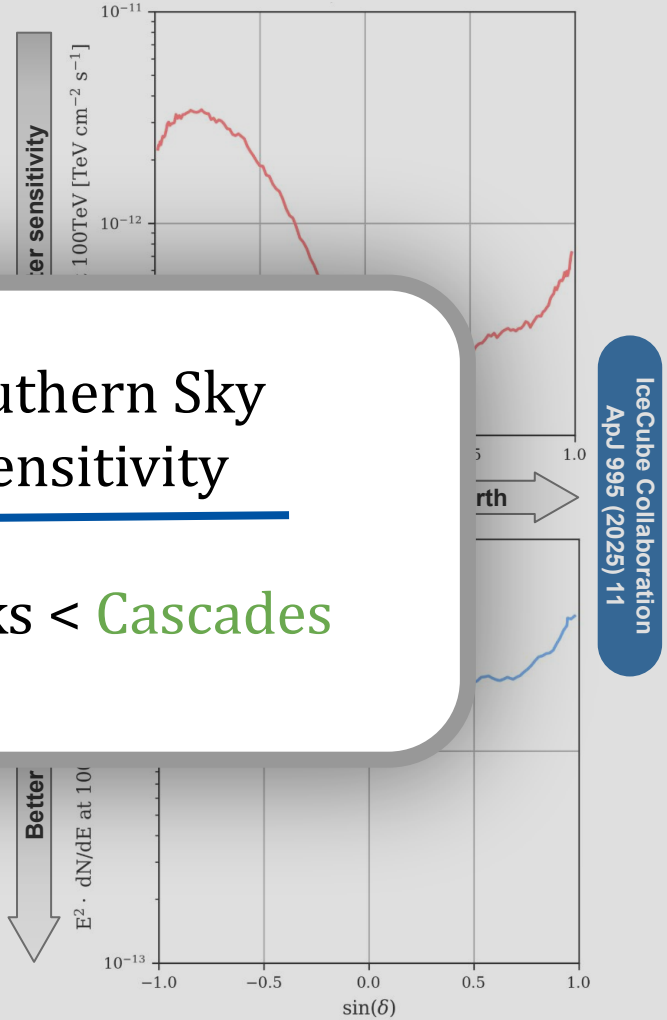
Southern Sky background μ

Northern Sky Sensitivity	Southern Sky Sensitivity
Tracks > Cascades	Tracks < Cascades

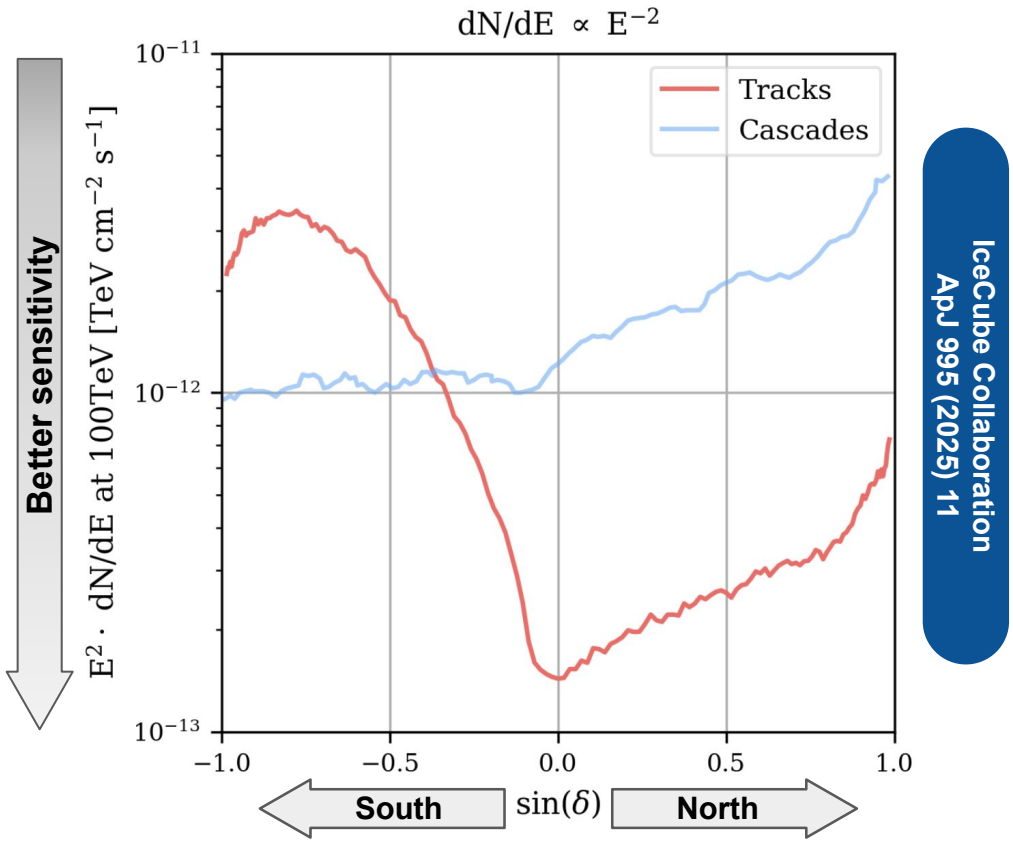
necessary in Southern Sky



Cascade-Based



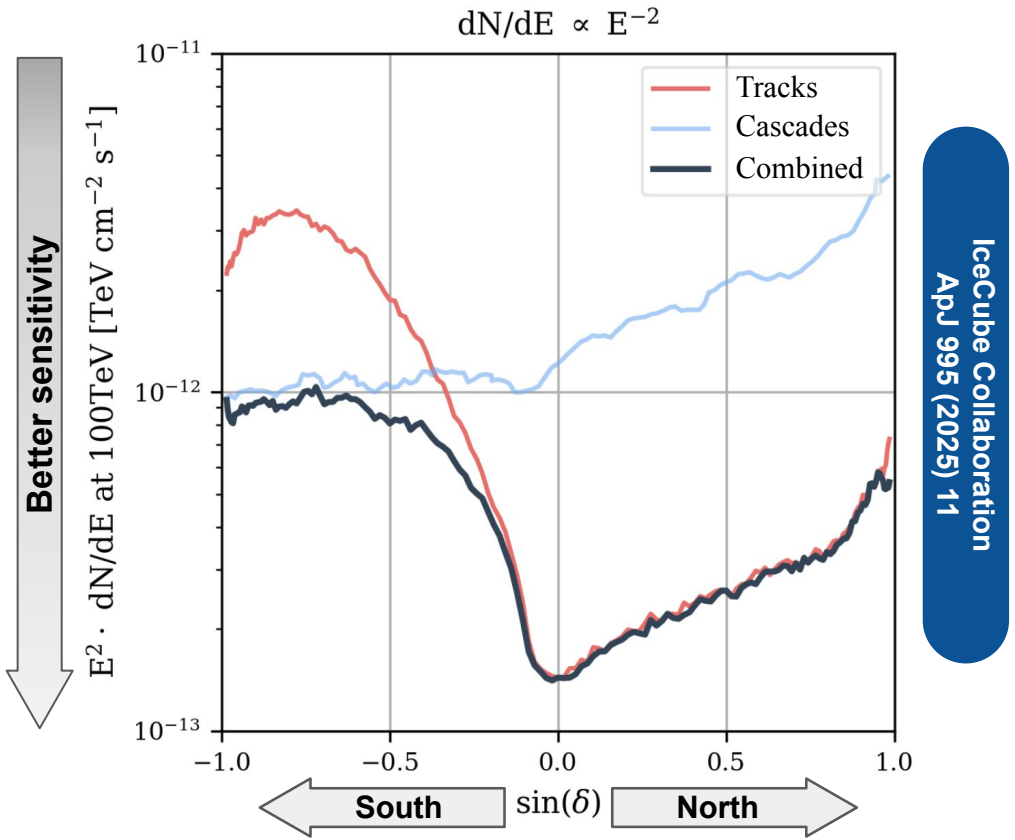
Simultaneous Fit: Sensitivity Improvement



Simultaneous Fit: Sensitivity Improvement

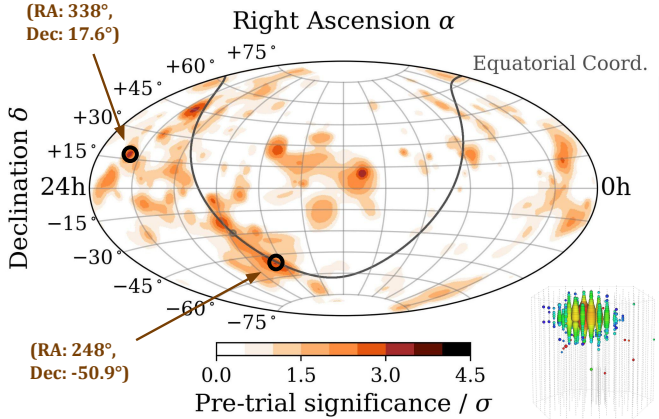
★ Results in **best** all-sky sensitivity

★ **Improvement in south** over both single-signature datasets



Simultaneous Fit: All-Sky Map

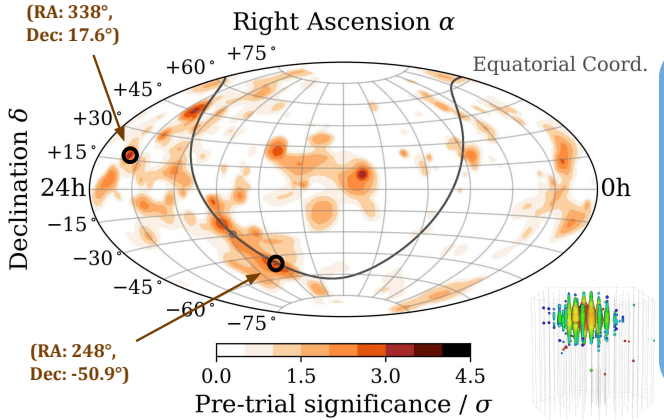
Cascades



IceCube Collaboration
Science 380 (2023) 1338-1343

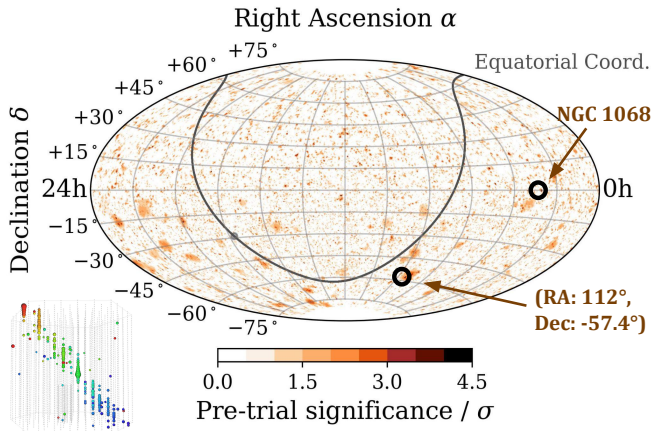
Simultaneous Fit: All-Sky Map

Cascades



IceCube Collaboration Science 380 (2023) 1338-1343

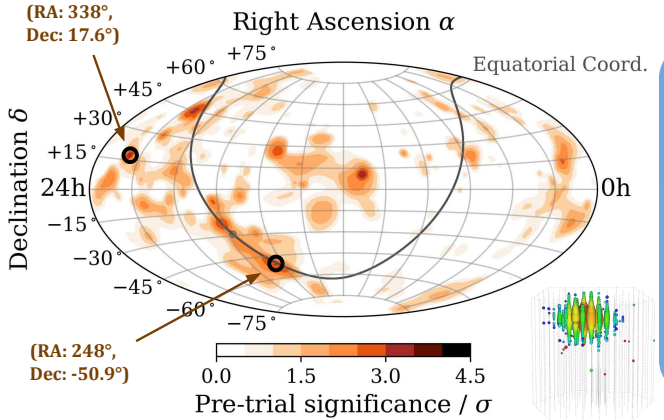
Tracks



IceCube Collaboration ApJ 995 (2025) 11

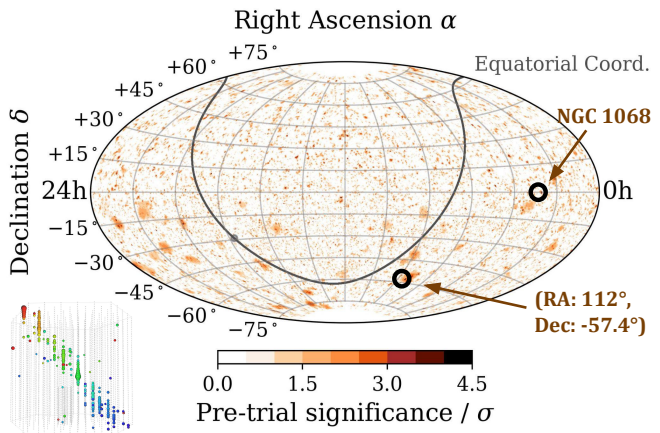
Simultaneous Fit: All-Sky Map

Cascades



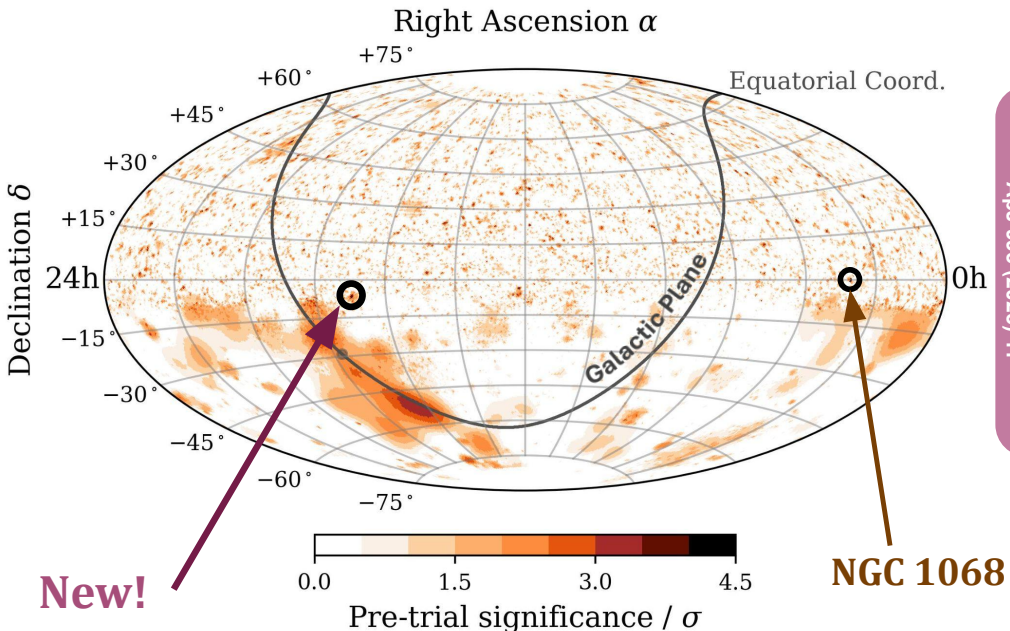
IceCube Collaboration Science 380 (2023) 1338-1343

Tracks



IceCube Collaboration ApJ 995 (2025) 11

Combined

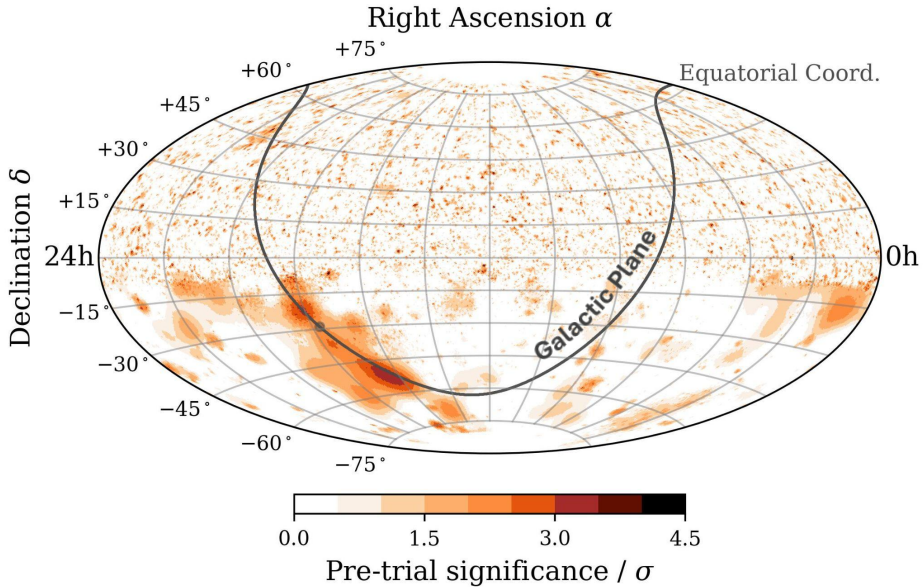


IceCube Collaboration ApJ 995 (2025) 11

Simultaneous Fit: Galactic Plane

- Combining event topologies increases significance (~5.9σ) compared to individual interaction channels
  - ➢ Even though GP in tracks channel alone is not significant (1.7σ)
- Constrains statistical flux errors better than individual topologies

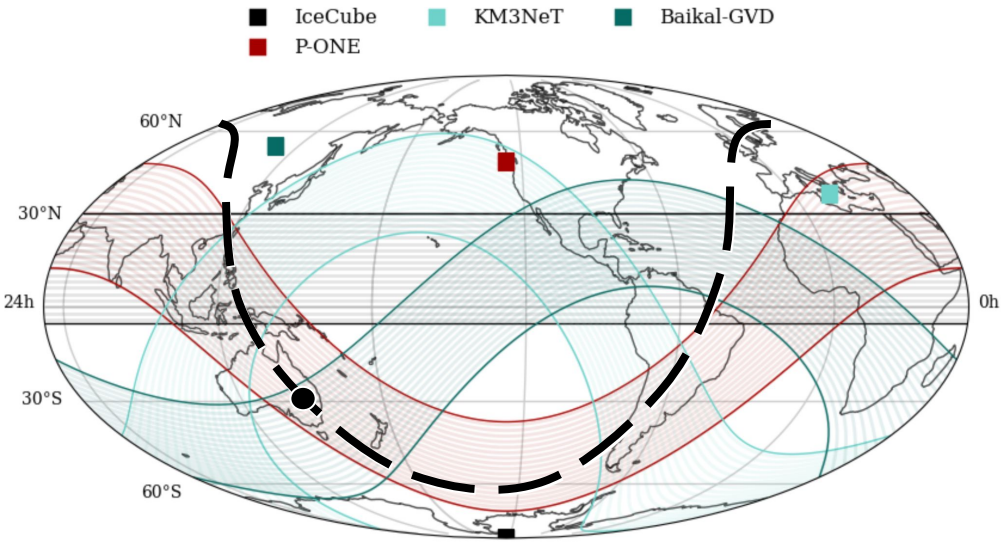
IceCube Collaboration
ApJ 995 (2025) 11



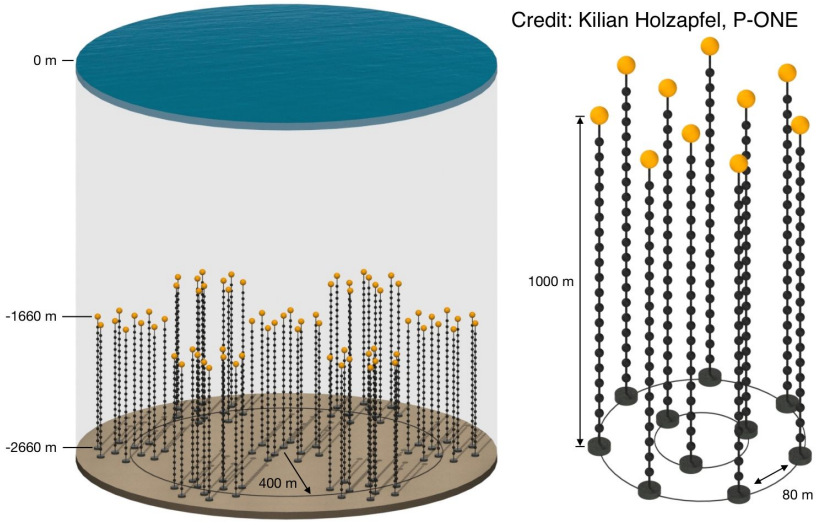
Future Experiments

Future Water-Cherenkov Detectors (>TeV)

- P-ONE
  - Uses Canadian deep sea network
  - Km^3-scale
  - *See talk by W. Kang*



Credit: L. Schumacher (FAU ErlangenNürnberg, ECAP)

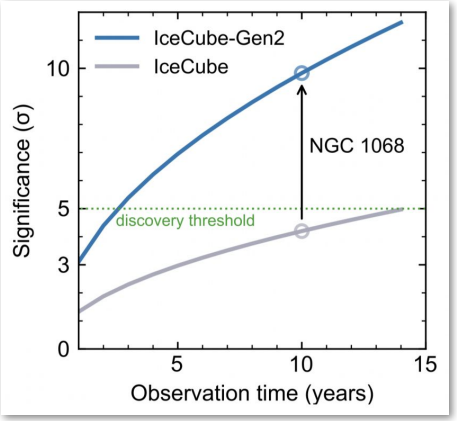


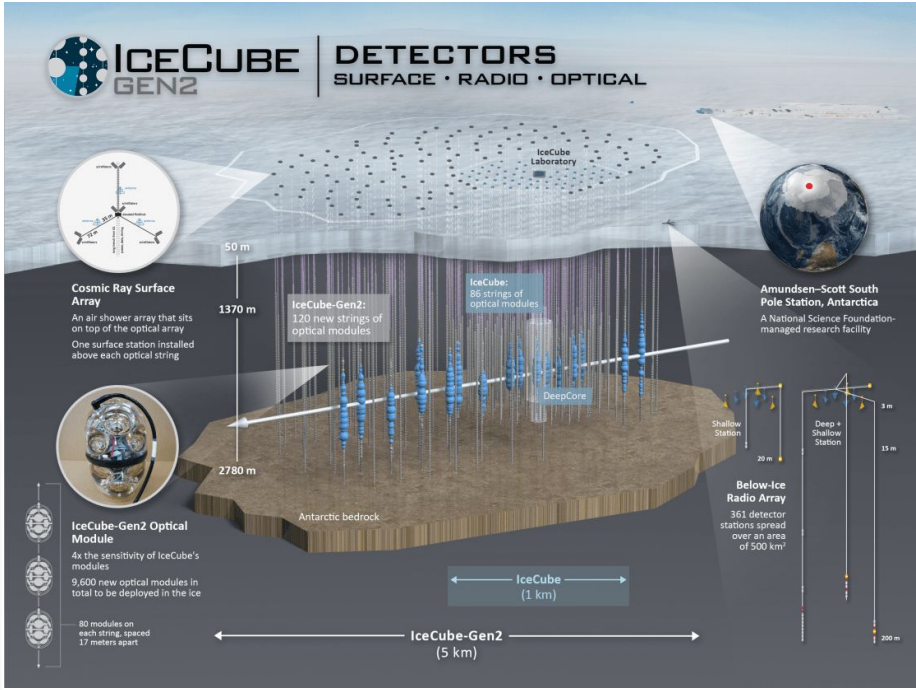
Credit: Kilian Holzapfel, P-ONE

Future Water-Cherenkov Detectors (>TeV)

- P-ONE
  - Uses Canadian deep sea network
  - Km^3-scale
  - *See talk by W. Kang*

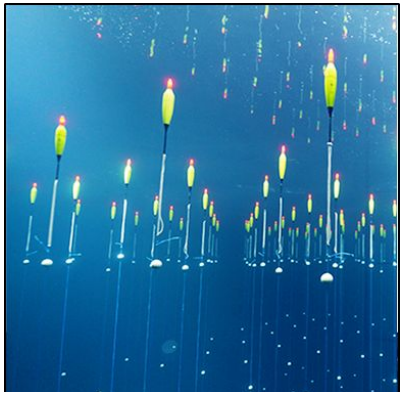
- IceCube-Gen2
  - Increase instrumented volume 8x
  - 5x improvement in effective area
  - 2x improvement in angular resolution
  - *See talk by J. Yanez*



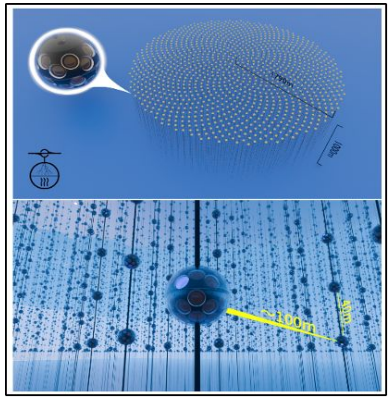


Future Water-Cherenkov Detectors (>TeV)

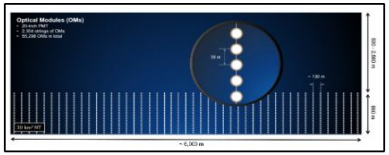
- P-ONE
  - Uses Canadian deep sea network
  - Km^3-scale
  - *See talk by W. Kang*
- IceCube-Gen2
  - Increase instrumented volume 8x
  - 5x improvement in effective area
  - 2x improvement in angular resolution
  - *See talk by J. Yanez*
- Trident, Neon, HUNT
  - Chinese initiatives
  - > Km^3-scale



Trident



Neon

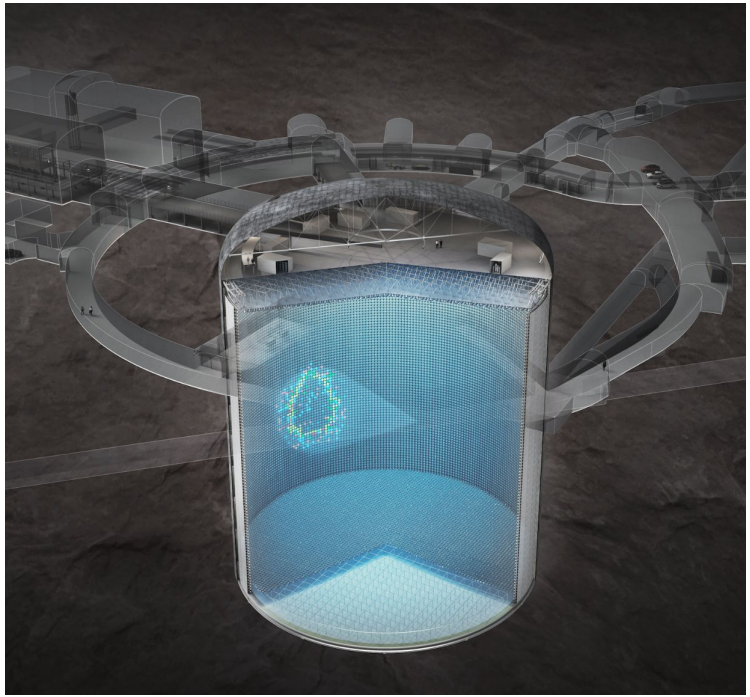




HUNT

Future Water-Cherenkov Detectors (>TeV)

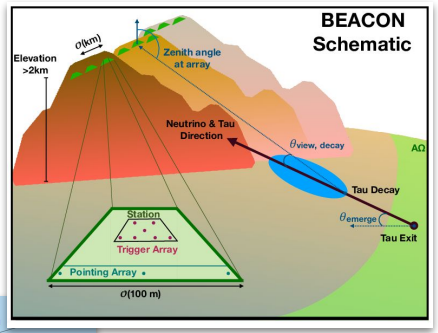
- P-ONE
  - Uses Canadian deep sea network
  - Km^3-scale
  - *See talk by W. Kang*
- IceCube-Gen2
  - Increase instrumented volume 8x
  - 5x improvement in effective area
  - 2x improvement in angular resolution
  - *See talk by J. Yanez*
- Trident, Neon, HUNT
  - Chinese initiatives
  - > Km^3-scale
- Hyper-Kamiokande
  - Successor to Super-Kamiokande
  - Developing high-energy astro program
  - *See talks by C. Bronner, R. Kralik, & L. Perisse*

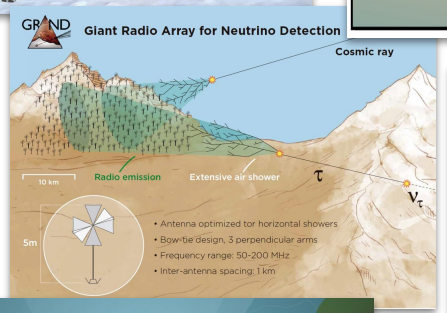


Current and Future* Air Shower, Radio, & Balloon Experiments (>100PeV)

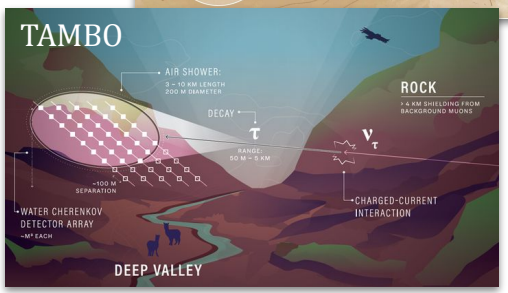
- Pierre Auger Observatory, GRAND*, BEACON*, Trinity*, TAMBO*
  - Earth-skimming $\nu_\tau \rightarrow$ air shower
  - *See TAMBO talk by J. Bazo*







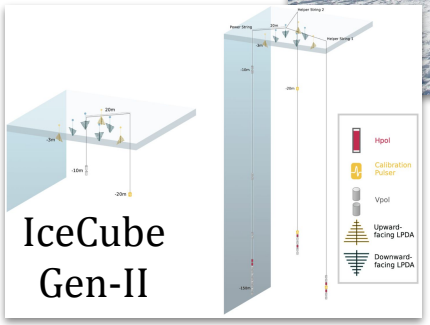




Current and Future* Air Shower, Radio, & Balloon Experiments (>100PeV)

- Pierre Auger Observatory, GRAND*, BEACON*, Trinity*, TAMBO*
  - Earth-skimming $\nu_\tau \rightarrow$ air shower
  - *See TAMBO talk by J. Bazo*
- ARA, ARIANNA*, RNO-G*, IceCube Gen-II*
  - Radio in ice
- PUEO
  - Balloon over ice









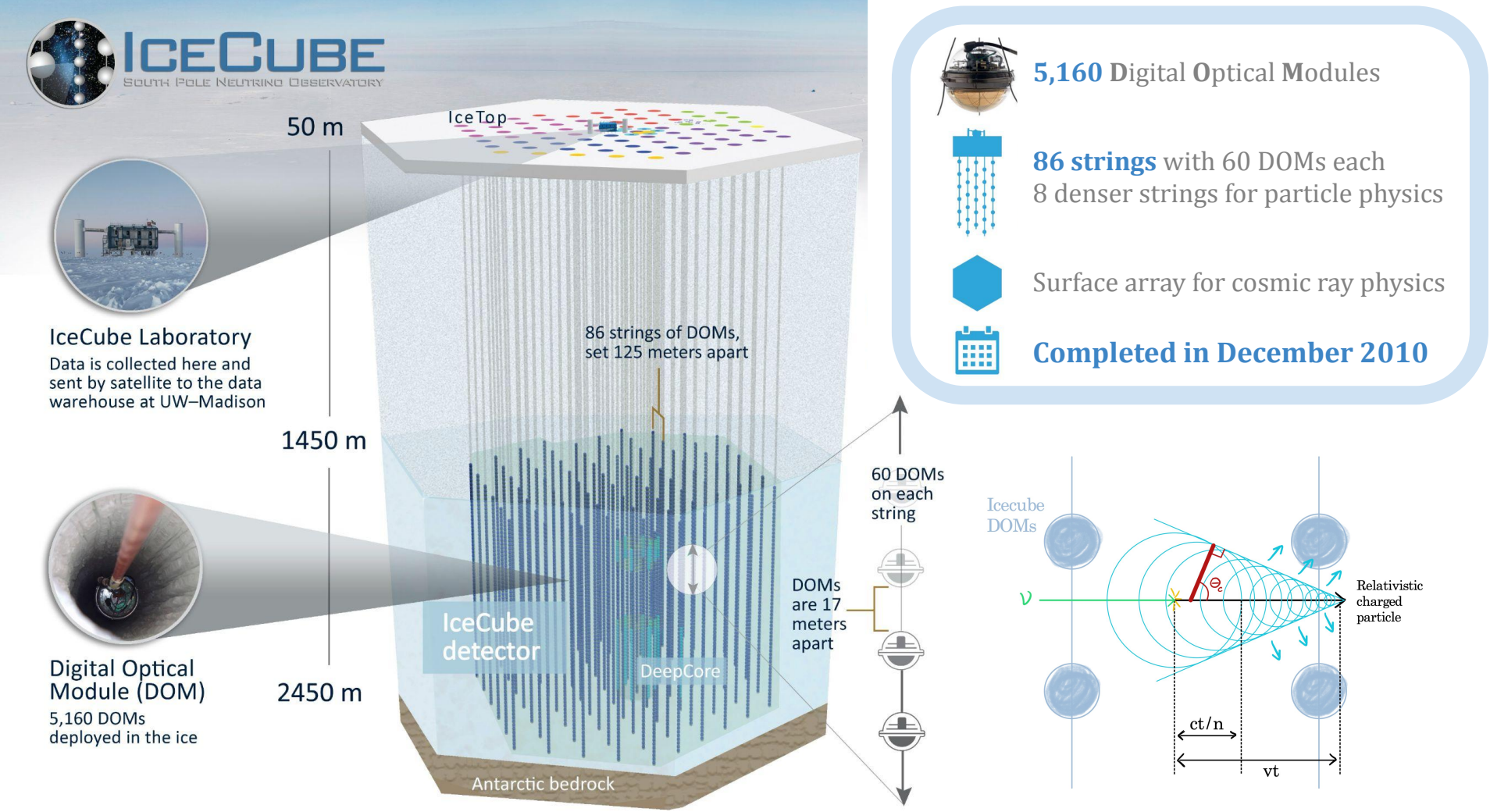


Summary

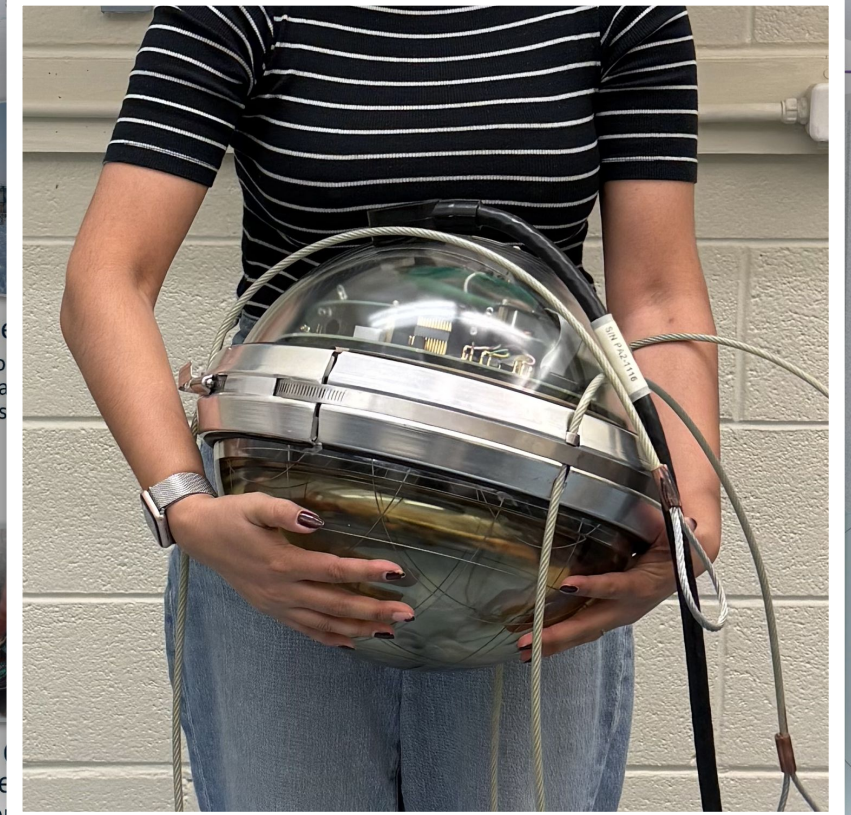
- Much work has been done so far to uncover neutrino spectrum
  - Flavor studies too!
- Various neutrino sources have been identified 13yrs after the discovery of high-energy astrophysical neutrinos by IceCube
  - **Galactic Plane emerges as first high-energy astrophysical neutrino source over 5σ!**
  - **> 100 PeV neutrino detected by KM3NeT**
  - Steady NGC 1068 (4.0σ)
  - Flaring TXS 0506+056 (3.0σ)
  - Emerging steady sources CGCG 420-015 & NGC 4151

- Exciting prospects with many new detectors in construction!

Supplementary Material


IceCube
South Pole Neutrino Observatory
50 m
IceTop
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
1450 m
86 strings of DOMs, set 125 meters apart
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock
5,160 Digital Optical Modules
86 strings with 60 DOMs each
8 denser strings for particle physics
Surface array for cosmic ray physics
Completed in December 2010
Icecube DOMs
ν
θc
Relativistic charged particle
ct/n
vt

IceCube



5,160 Digital Optical Modules

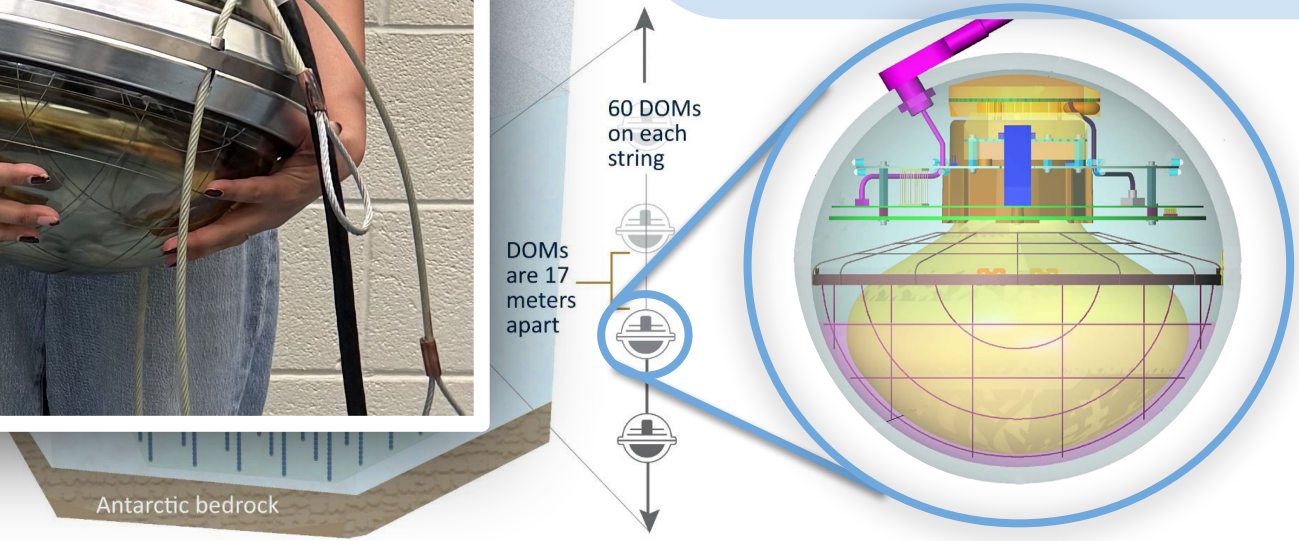
86 strings with 60 DOMs each
8 denser strings for particle physics

Surface array for cosmic ray physics

Completed in December 2010

IceCube
Data is co
sent by sa
warehous

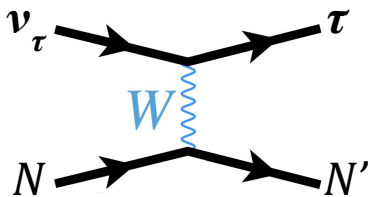
Digital
Module
5,160 DO
deployed in the ice



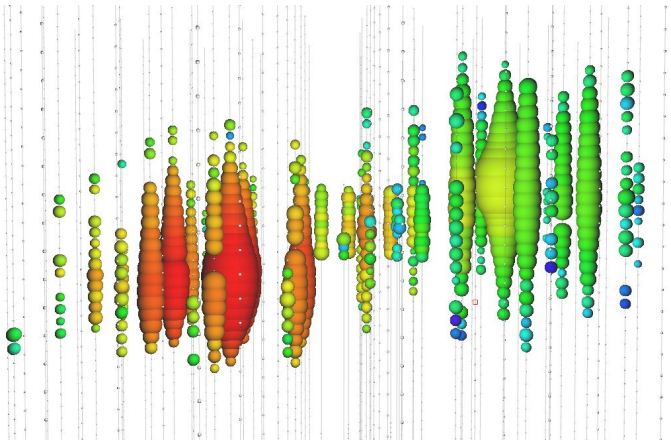
IceCube Event Signatures - Tau Neutrinos

Double Bang

- Limited phase space for detection
- $\lambda_\tau \simeq \frac{50\ \text{m}}{1\ \text{PeV}} E_\tau$
- Hard to distinguish from single cascade



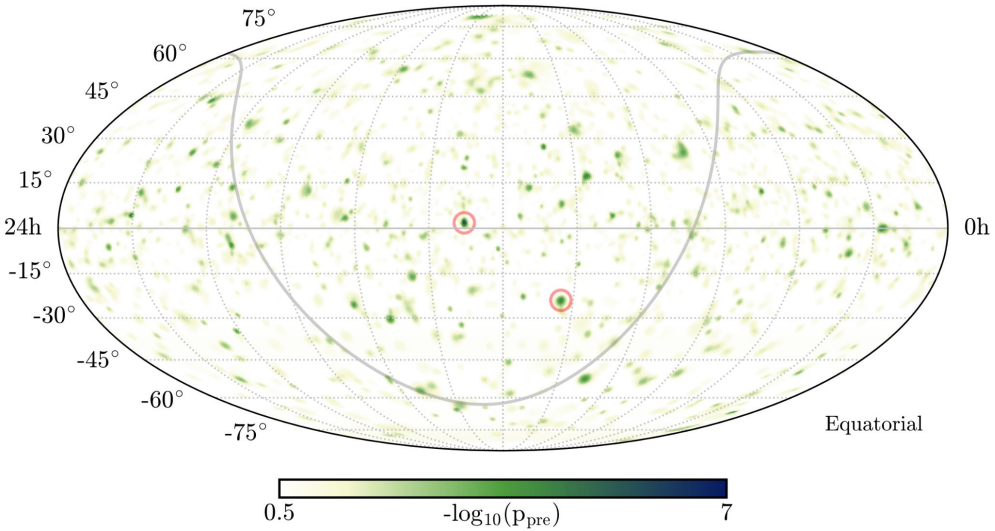
Simulated 10 PeV Double Bang Event



Early Late

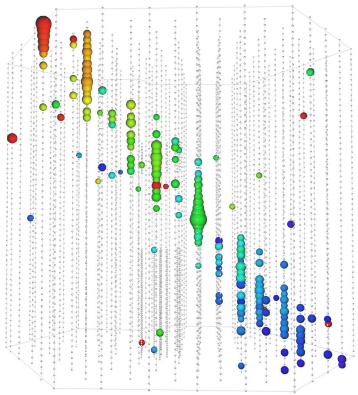
Recent Point-Source Search Results

IceCube Collaboration
ApJ 988 (2026) 37



Early Starting Tracks Event Sample

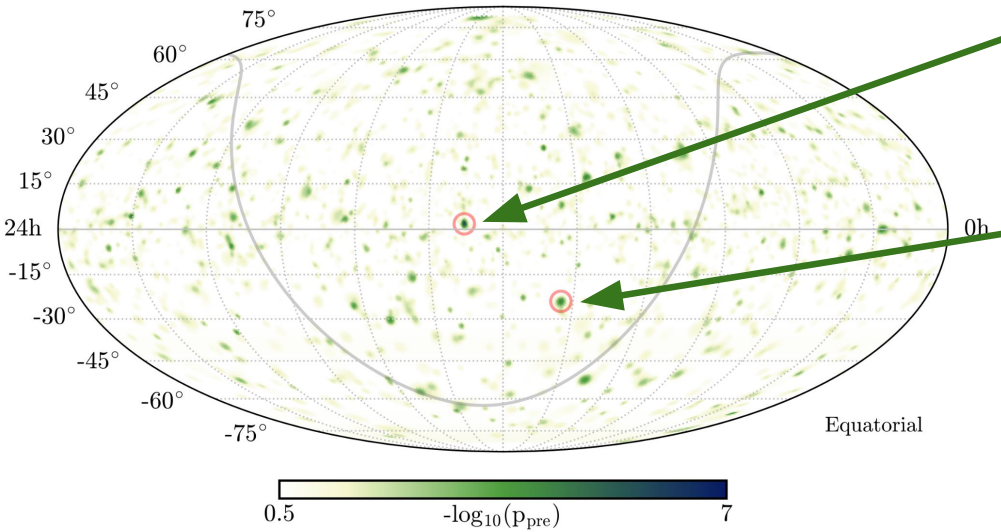
- 10yrs of data
- Includes only starting tracks
- Higher astrophysical purity through rejection of atmos. μ and ν



How can we improve track sensitivity in the southern hemisphere?

Recent Point-Source Search Results

IceCube Collaboration
ApJ 988 (2026) 37



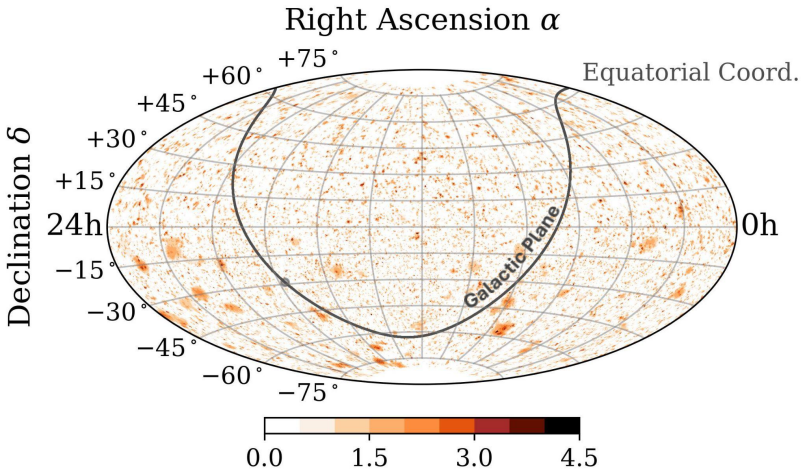
(RA: 195.64°, Dec: 1.79°)

(RA: 155.21°, Dec: -23.97°)

*** Both spots consistent with null hypothesis after corrections**

Recent Point-Source Search Results

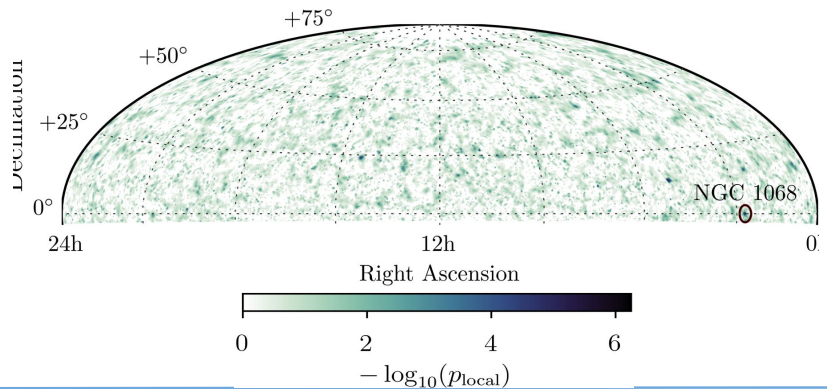
IceCube Collaboration ApJ 995 (2025) 11



Point-Source Tracks

- 13yrs of data
- Includes through-going, starting, and stopping tracks

IceCube Collaboration ApJL 1000 (2026) L26

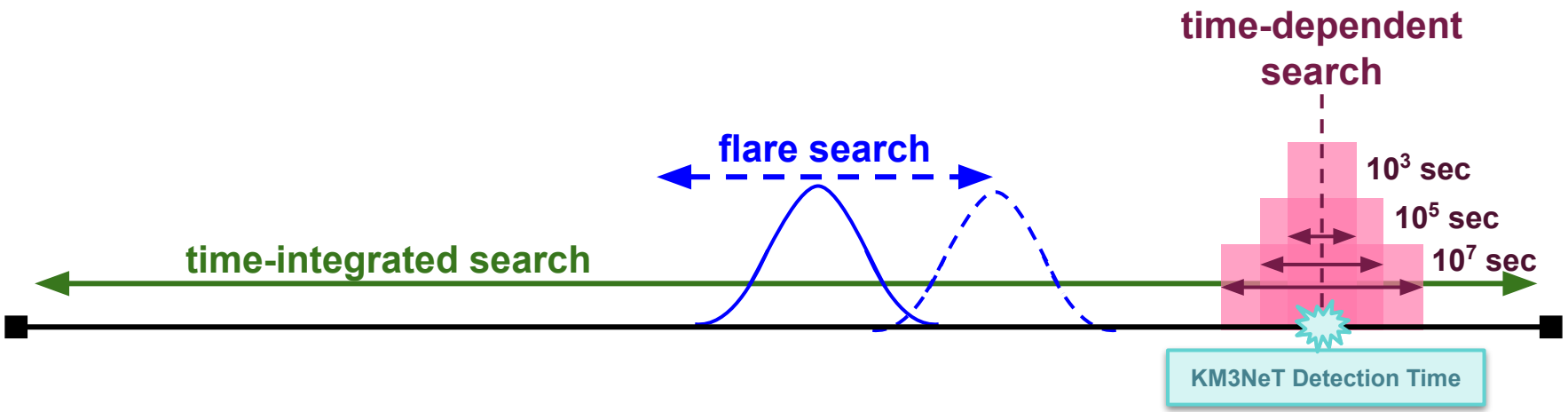


Northern Tracks

- 13yrs of data
- Includes through-going, starting, and stopping tracks
- Reprocessed data to include updated systematics
- Improved direction & energy reconstruction

IceCube Follow-Up of the KM3NeT EHE Event

1. Non-GFU (Gamma-ray follow-up) Detection of KM3-230213A
2. Time-dependent and time-integrated search for neutrinos
3. Flare search for neutrinos



IceCube Follow-Up of the KM3NeT EHE Event

